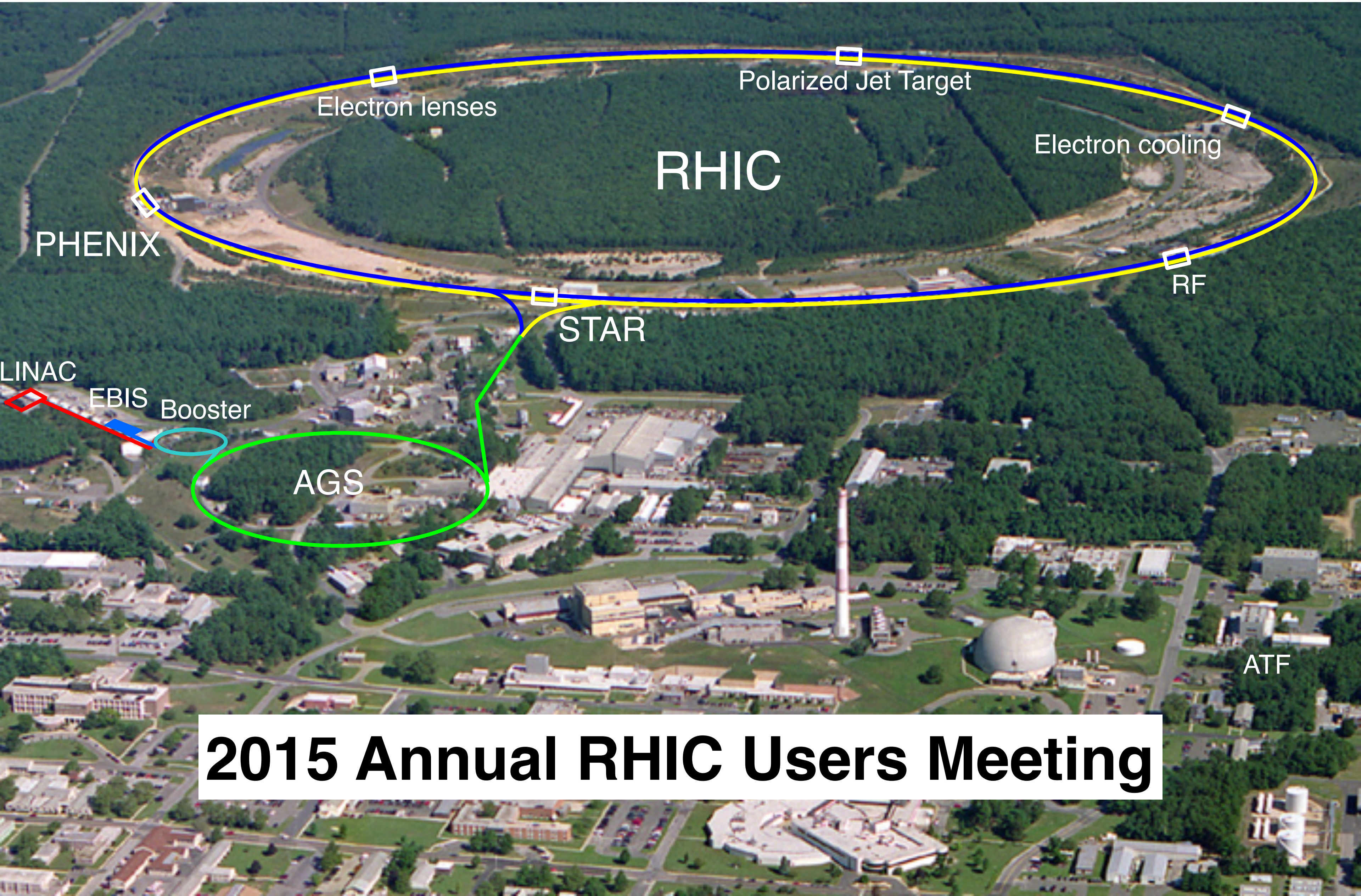
Completing the RHIC Science Mission



2015 Annual RHIC Users Meeting

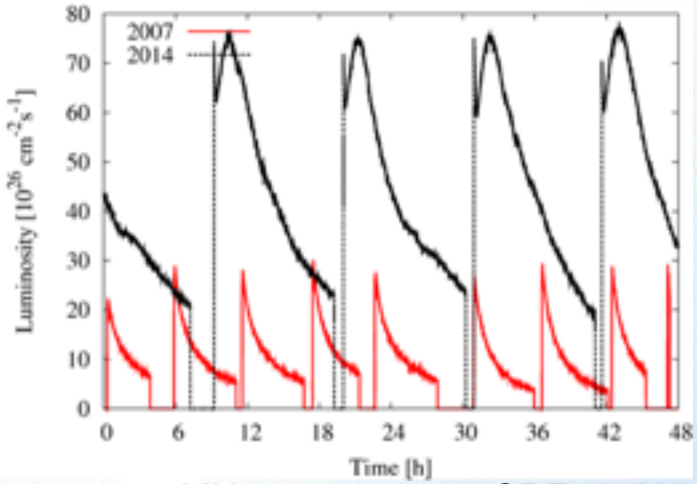
The Facility

RHIC – the First Heavy Ion Collider

- After continuous improvements and upgrades RHIC reached 25x design luminosity, exceeding "RHIC II" goal, 3 years early & at 1/7 of estimated cost
- Unparalleled flexibility of operation:
  - Wide energy range ($\sqrt{s_{NN}}$ = 7 – 200 GeV)
  - Capability of colliding different species with detector in center-of-mass frame
  - 6 modes (Au+Au, d+Au, Cu+Cu, Cu+Au, U+U, ^{3}He+Au) and 15 energies to date
- Ongoing upgrades:
  - 56 MHz SRF cavity to compress vertex and increase usable luminosity (commissioned)
  - Low Energy RHIC electron Cooling: 3 – 10x Au-Au luminosity for $\sqrt{s_{NN}} < 20$ GeV

BNL Electron Beam Ion Source

Au-Au luminosity with 3-D cooling



56 MHz quarter wave SRF cavity

RHIC explores the Phases of Nuclear Matter

LHC: High energy collider at CERN with 13.8 - 27.5 times higher beam energy: Pb+Pb, p+Pb, p+p collisions only.

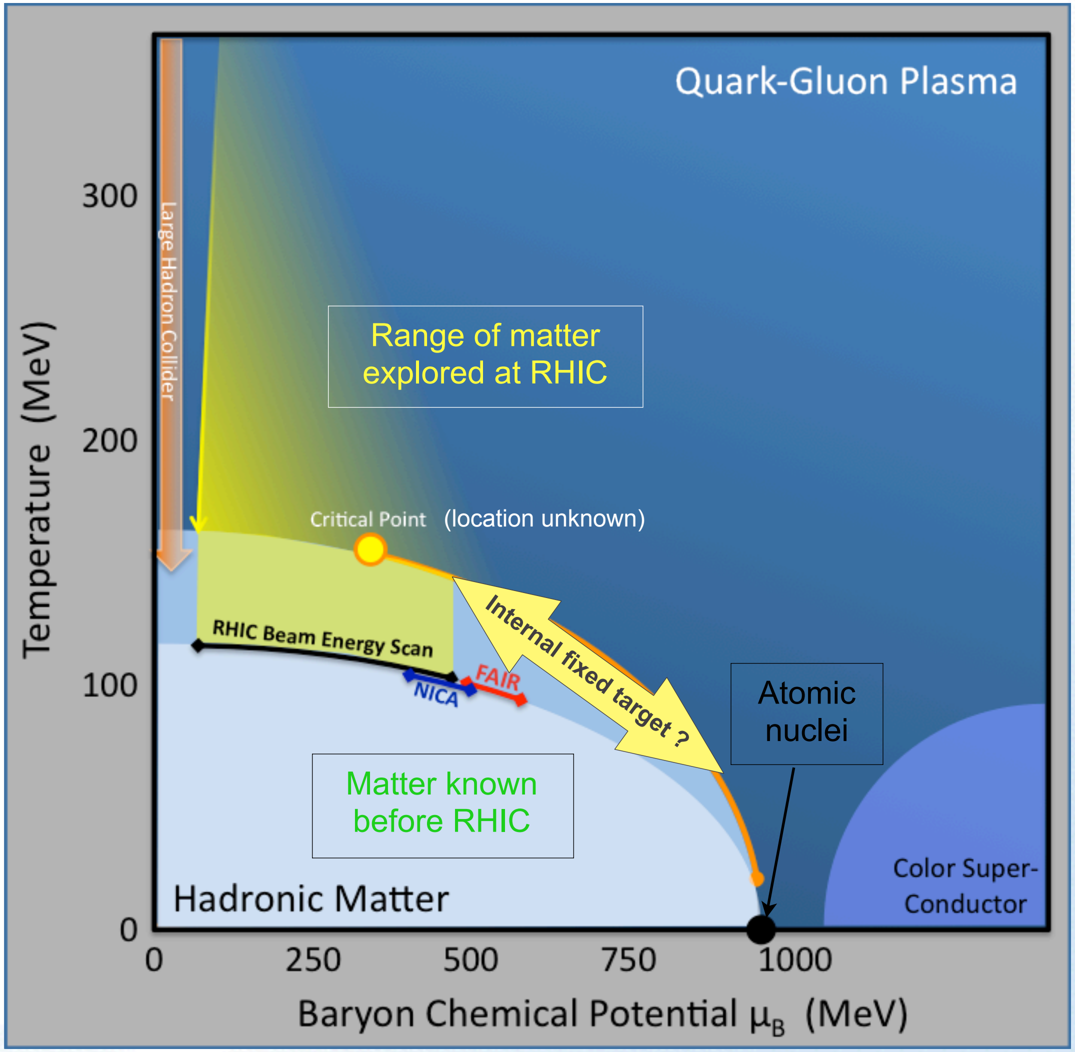
FAIR & NICA: Planned European facilities at lower energies.

RHIC: Spans largest swath of the phase diagram in the preferred collider mode.

Message

RHIC is perfectly suited to explore the phases of nuclear matter and the perfectly liquid quark-gluon plasma.

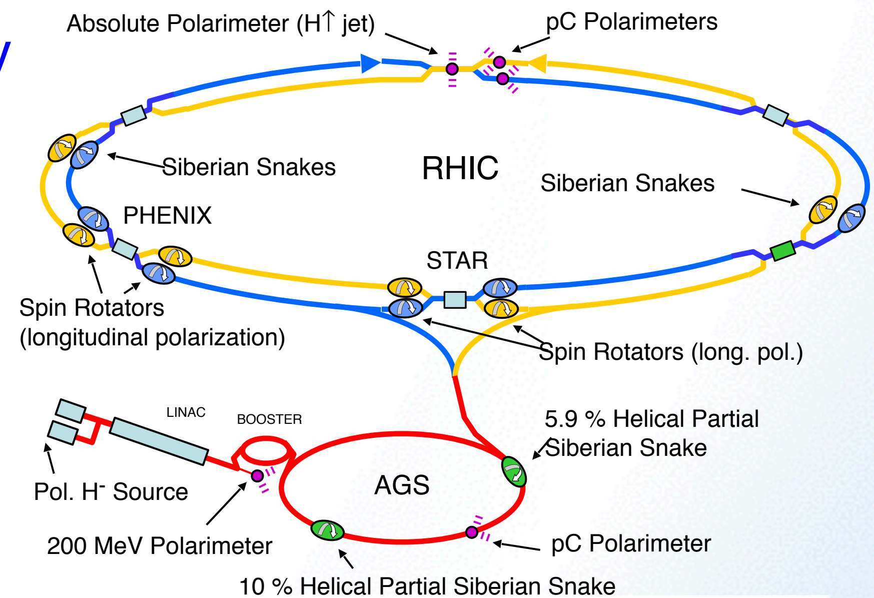
If RHIC did not exist, it would require a $2B+ investment to build a facility with comparable physics reach.



BROOKHAVEN NATIONAL LABORATORY

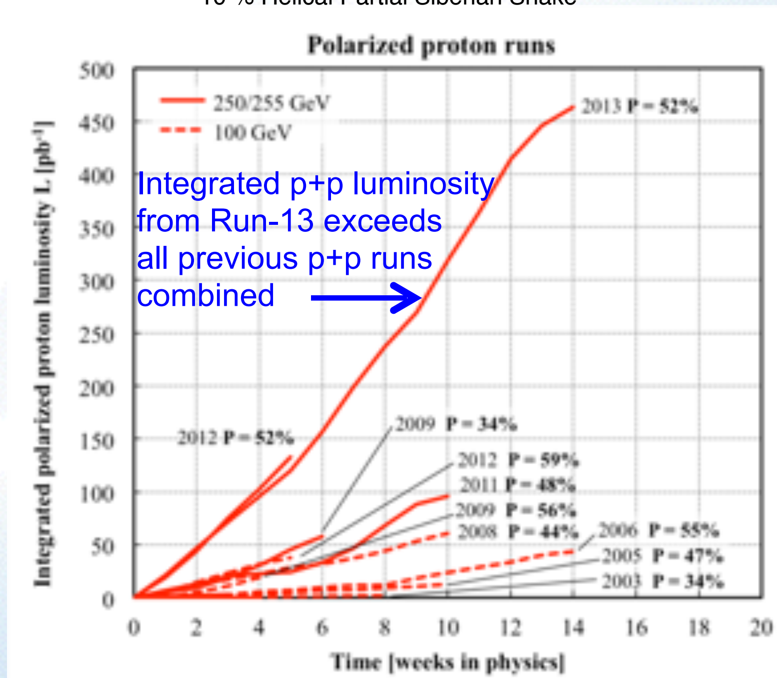
RHIC – the First Polarized Proton Collider

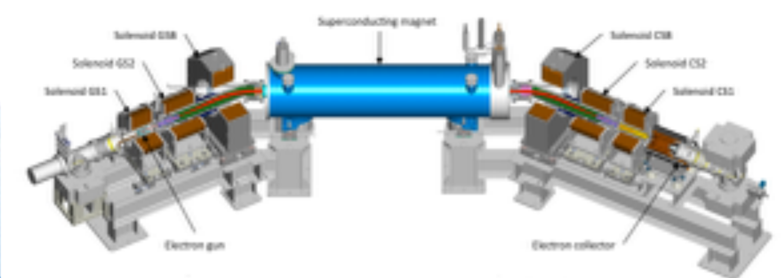
- Successful development of all necessary tools to accelerate polarized protons in the injector and in RHIC (polar. source, [partial] Siberian snakes, polarimeters)



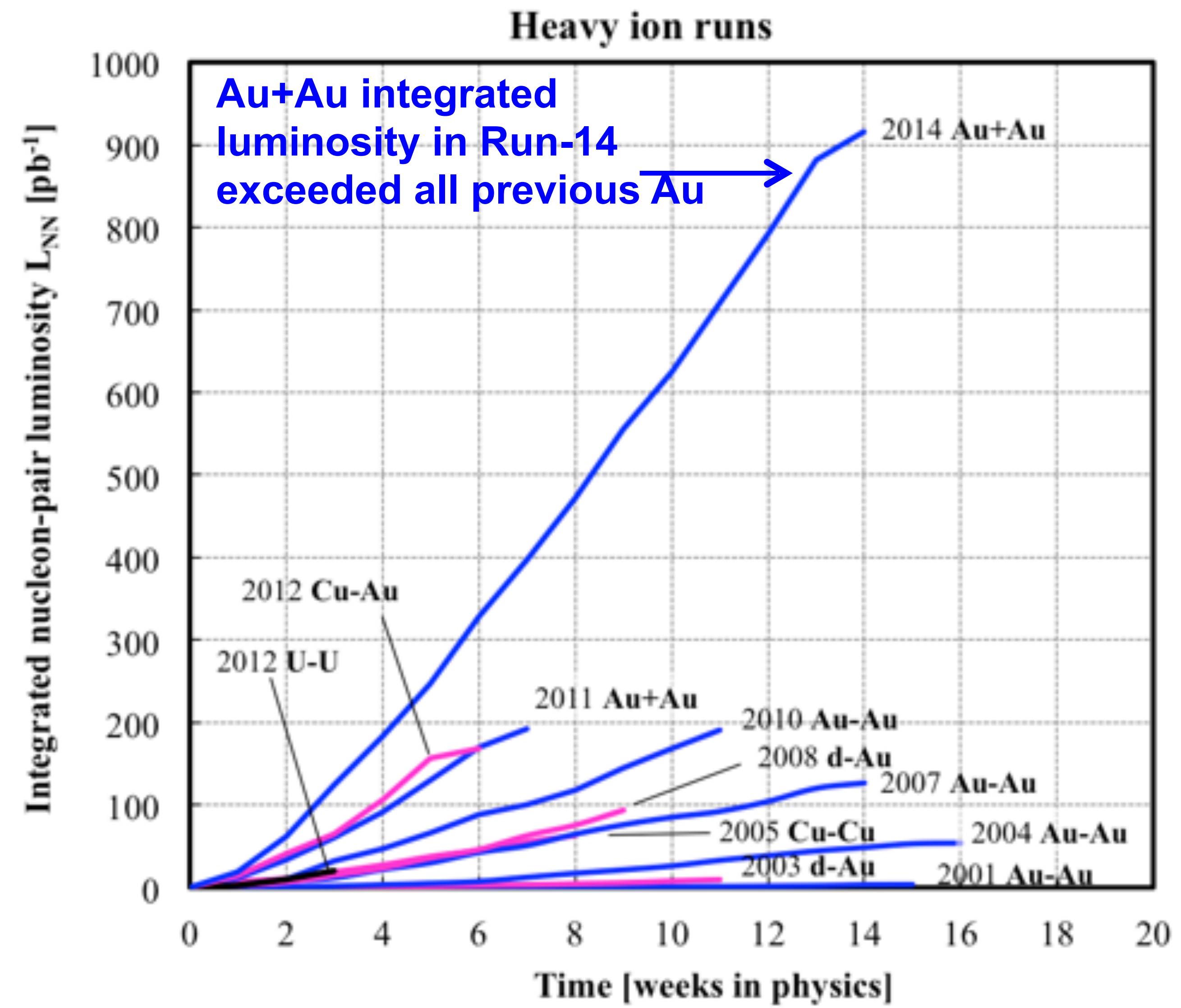
- Polarized proton collisions in RHIC:
  - $\sqrt{s}$=200 GeV: P~59%, L_{peak}~0.5×10^{32} $cm^{-2}s^{-1}$
  - $\sqrt{s}$=510 GeV: P~52%, L_{peak}~2.5×10^{32} $cm^{-2}s^{-1}$

- Luminosity increase with electron lenses Compensate for beam-beam interactions Successful operation in Run 15

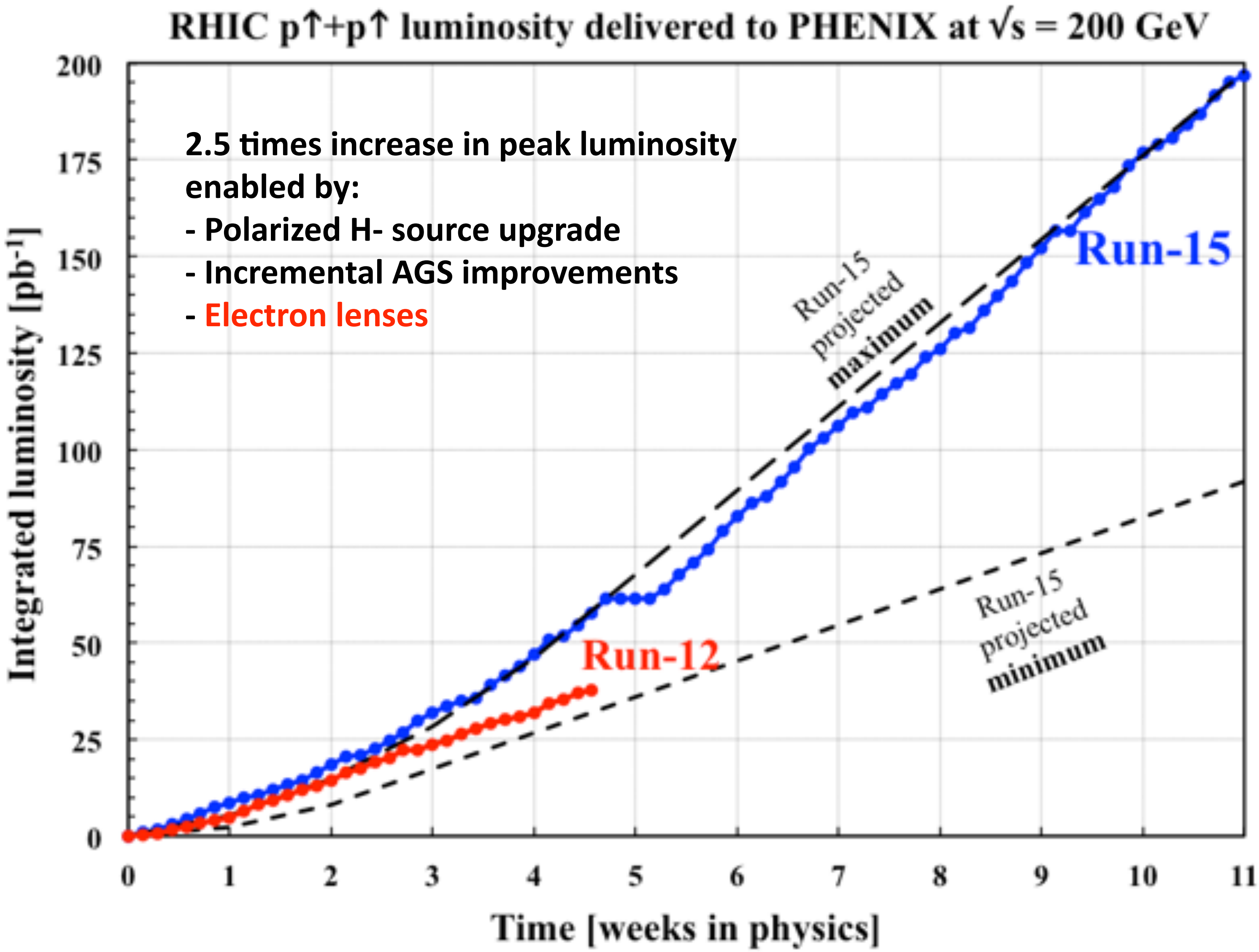




RHIC gets better and better…



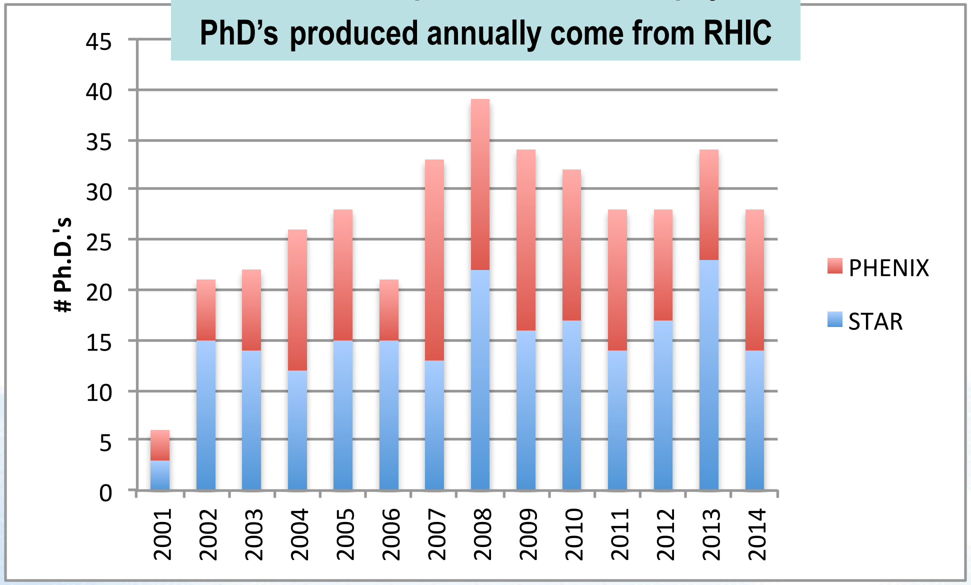
… and even better

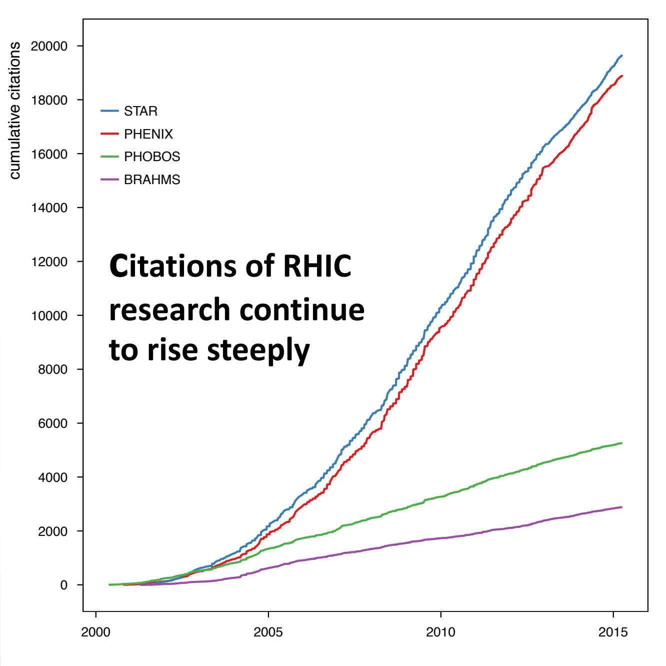


RHIC: Productivity and Impact

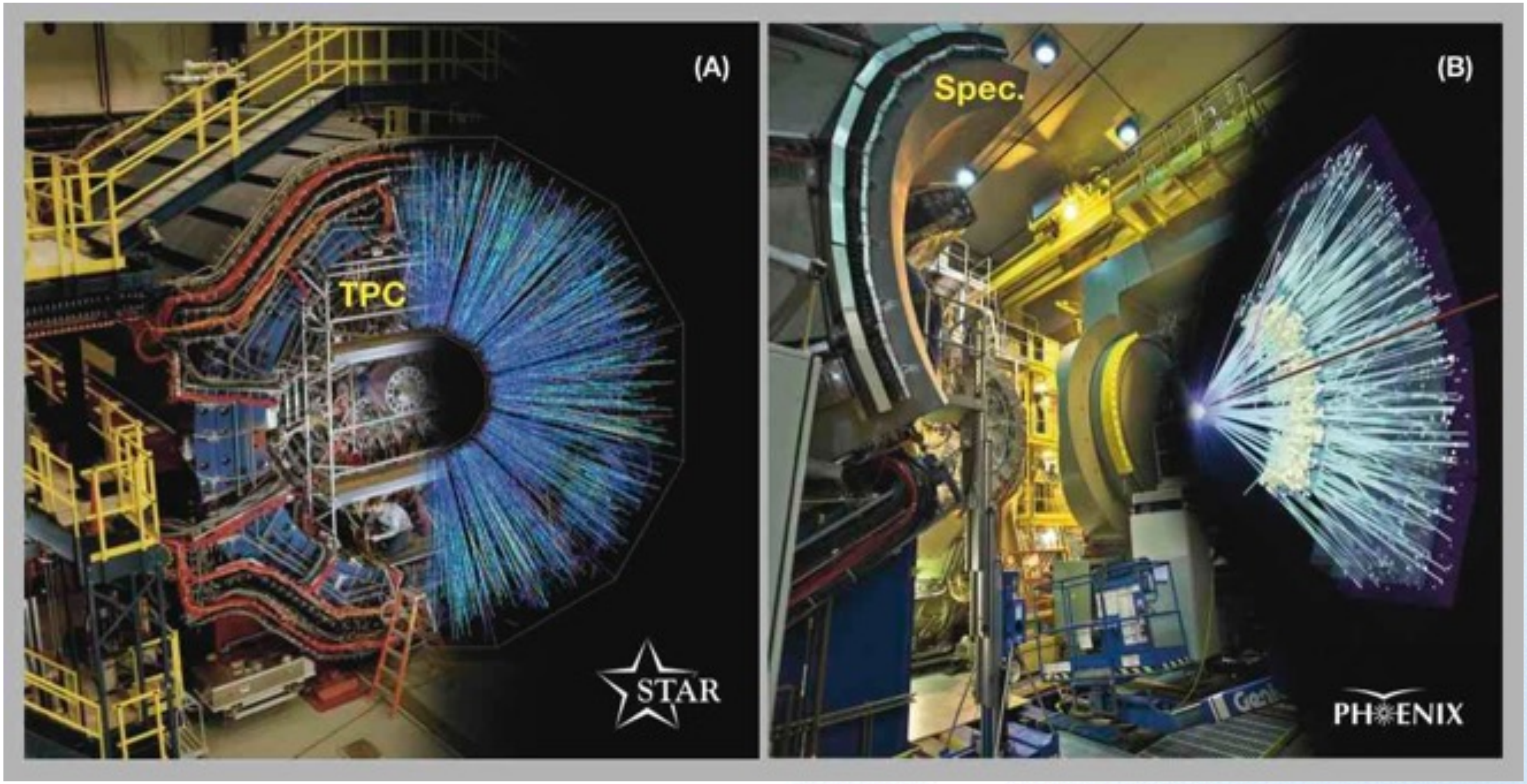
Collaboration	Total # Refereed Papers	Total # Citations for Ref'd Papers	# PRL's	# Citations for 2005 White Paper	Position Among Most Cited NP Papers 2001-14	# Papers with >250 Citations
PHENIX	142	18,812	66	1,923	4	17
STAR	171	19,673	65	2,008	3	19
PHOBOS	39	4,999	15	1,488	5	1
BRAHMS	22	3,477	10	1,462	6	3
Total	**374**	**46,961**	**156**	**5,943**	**4 in top 10**	**40**

About 40% of experimental nuclear physics PhD's produced annually come from RHIC





RHIC: The Detectors

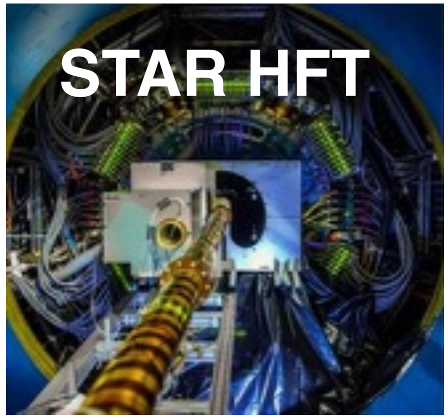


~580 collaborators from 13 countries

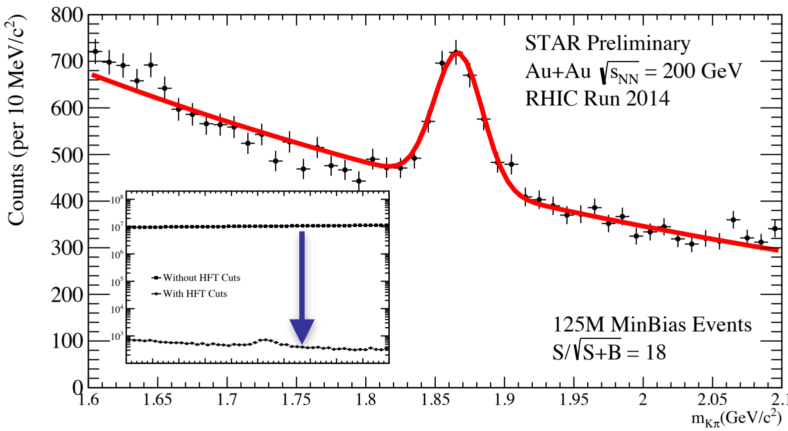
~550 collaborators from 15 countries

RHIC: Recent Detector Upgrades

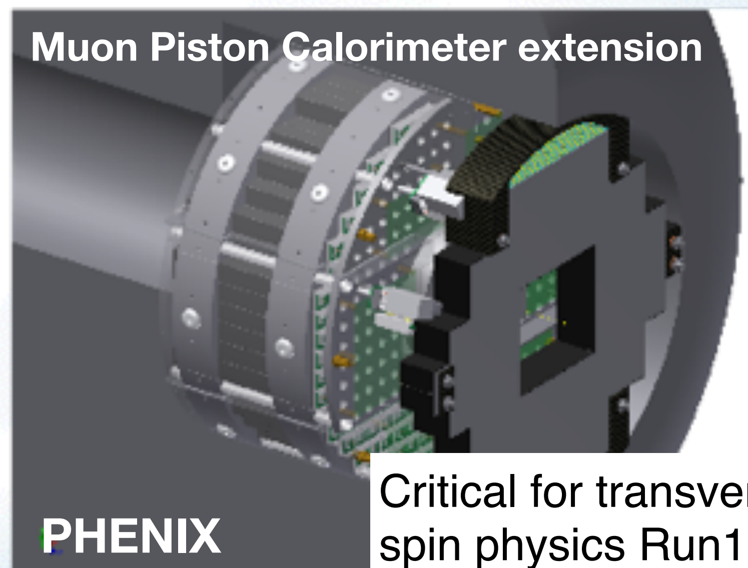
Fully reconstruct open charm/beauty hadrons with displaced vertex



Completed on schedule and below cost



Enhances triggering capabilities for heavy quarkonia



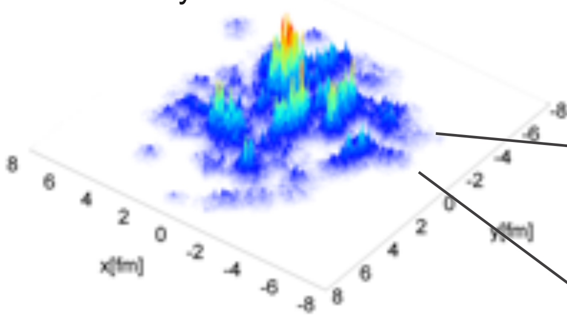
Critical for transverse spin physics Run15

The Science 2007-14

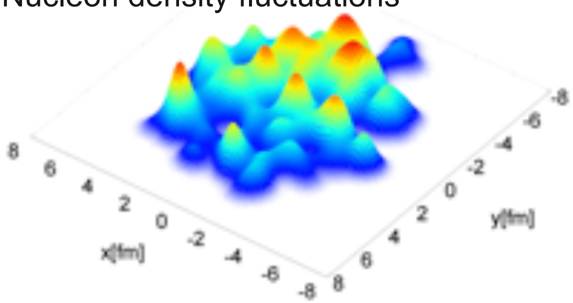
A whirlwind tour

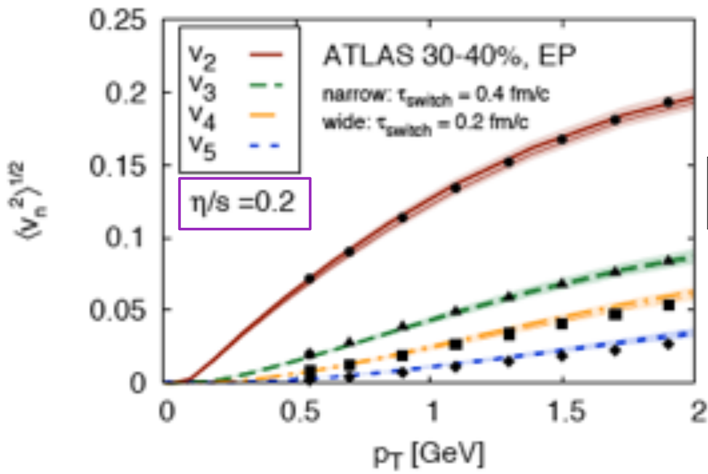
Beyond discovery: η/s

Gluon density fluctuations

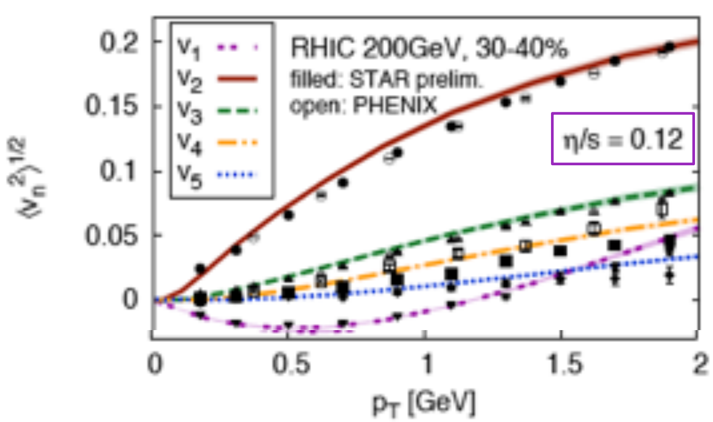


Nucleon density fluctuations





LHC



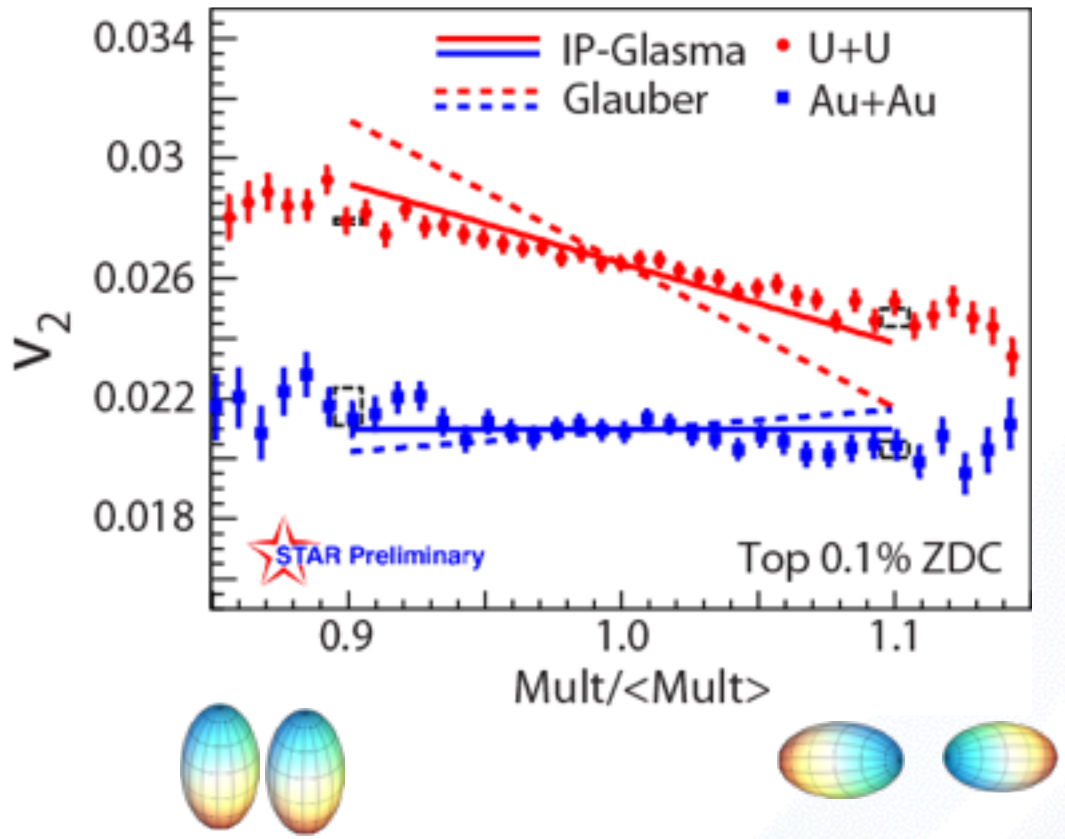
RHIC

η/s determination from data depends on assumption of the the scale of graininess of the density of the colliding nuclei.

Nucleon size (~1 fm) or gluon saturation scale ($1/Q_s \sim 0.1$ fm) ?

QGP @ RHIC is more strongly coupled than QGP@ LHC.

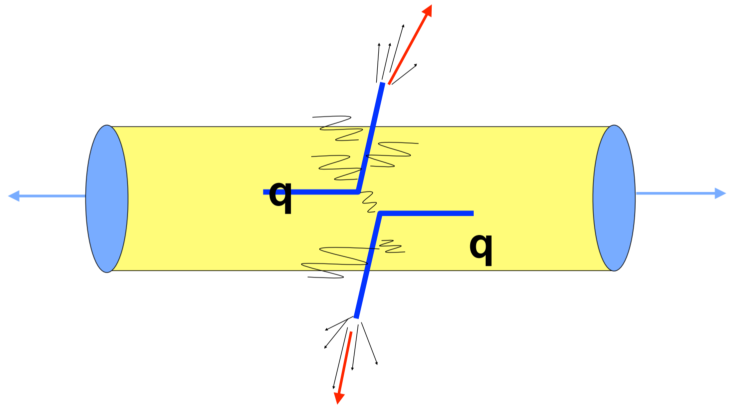
Shape Matters: U+U Collisions



IP-Glasma model, but not NN Glauber model consistent with the observations.

→ Initial state fluctuations occur at the parton level

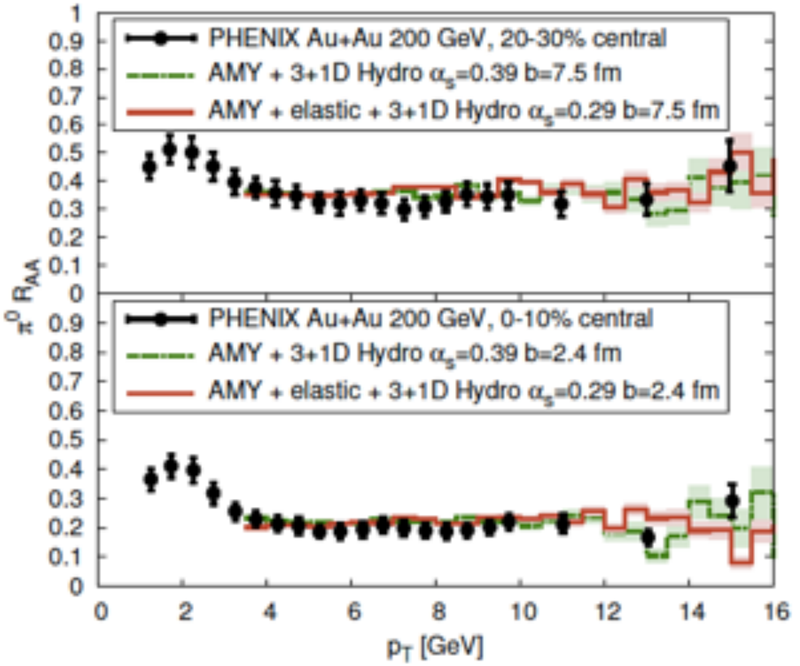
Jet quenching



Toward quantitative measurement of basic medium properties: *q-hat*

$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L \qquad \frac{dE}{dx} = -C_2 \hat{e}$$

Radiative Collisional



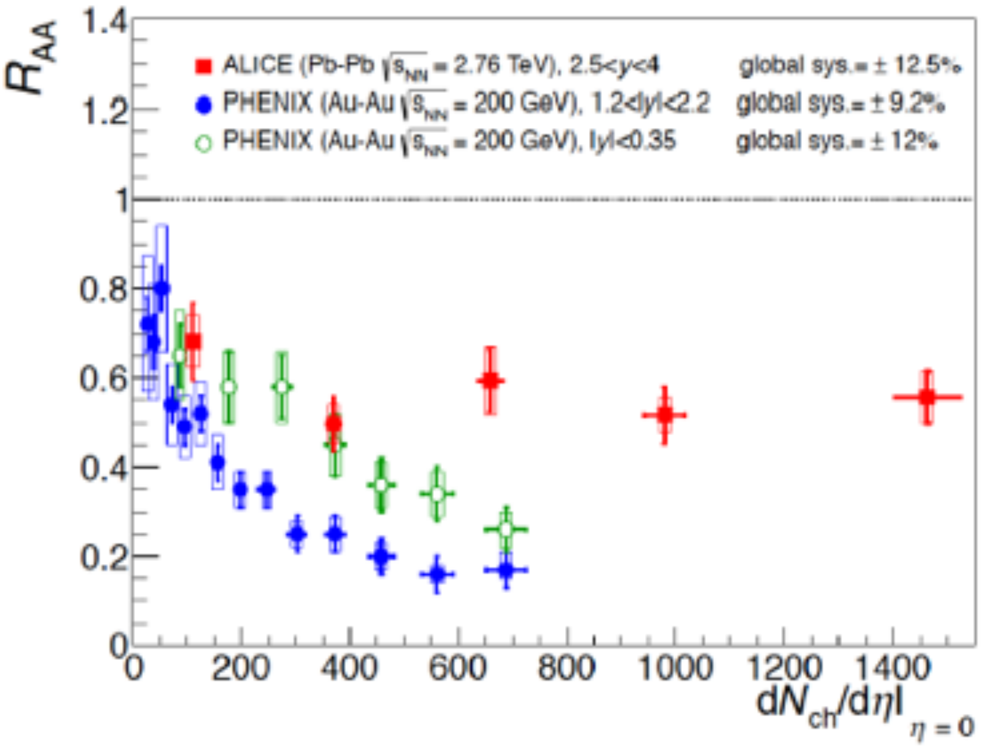
$\boxed{\text{JET Collaboration}}$

$$\frac{\hat{q}}{T^3} = \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC} \end{cases}$$

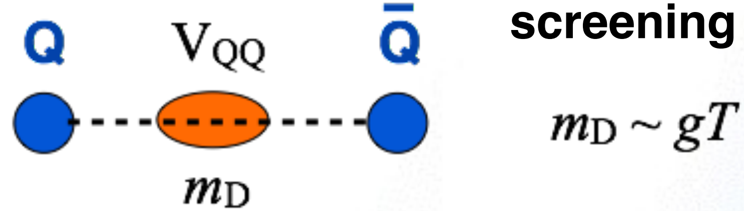
Phys. Rev. C 90 (2014) 014909

QGP @ RHIC is more strongly coupled than QGP@ LHC.

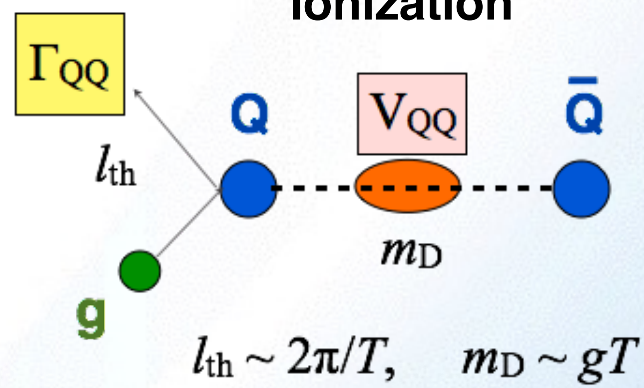
Quarkonium “melting”



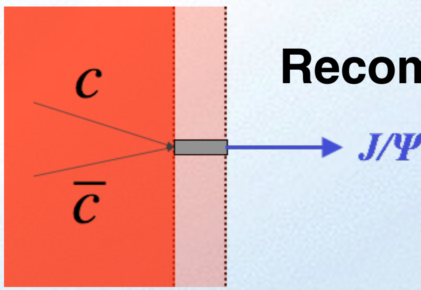
Color screening



Ionization



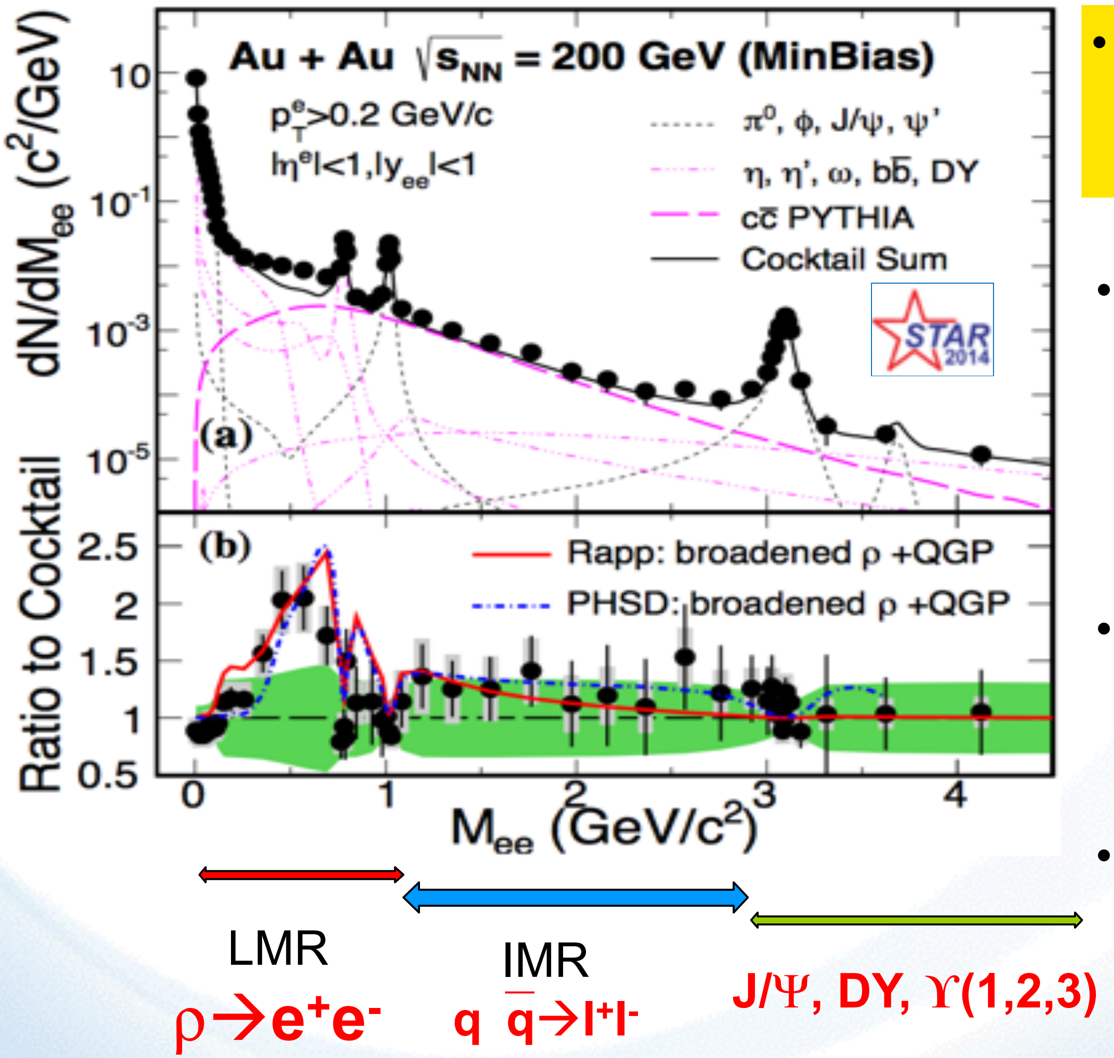
Recombination



All charmonium states melt in the QGP but can be regenerated by recombination when the charm quark density is high (at LHC).

Resolved measurement of Upsilon states required at RHIC.

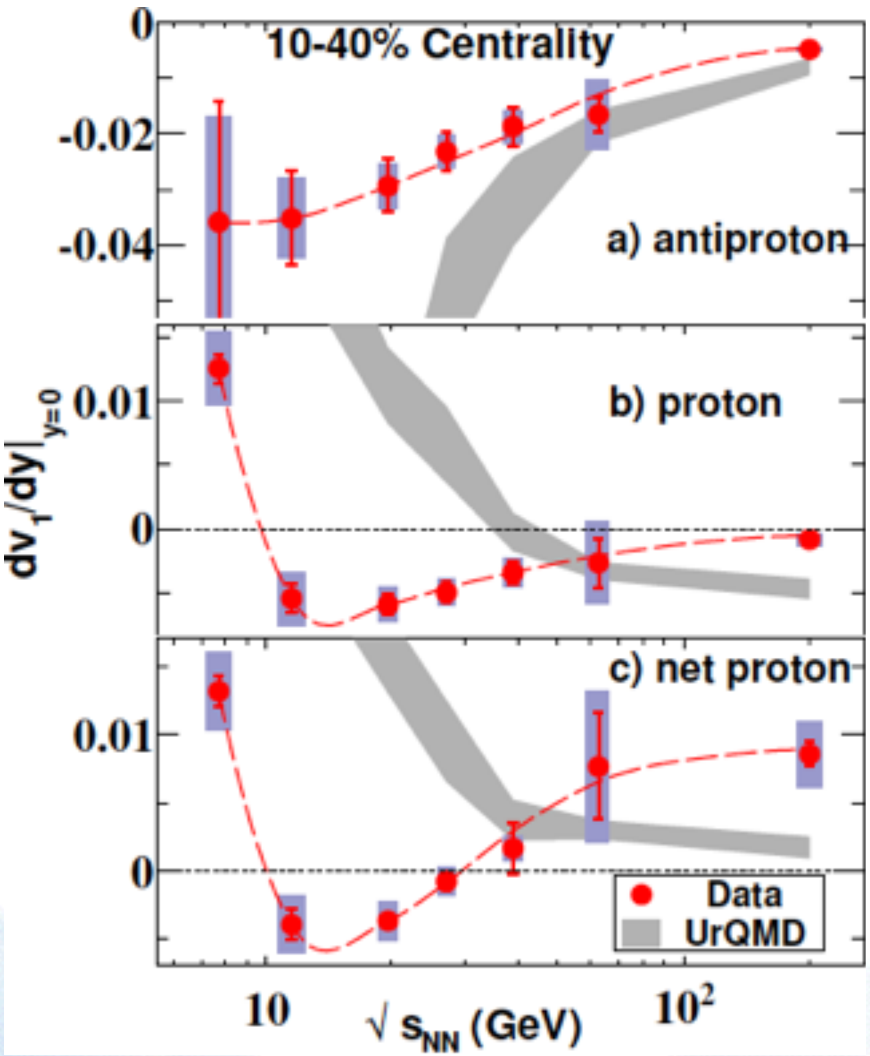
Dileptons: Chiral symmetry restoration



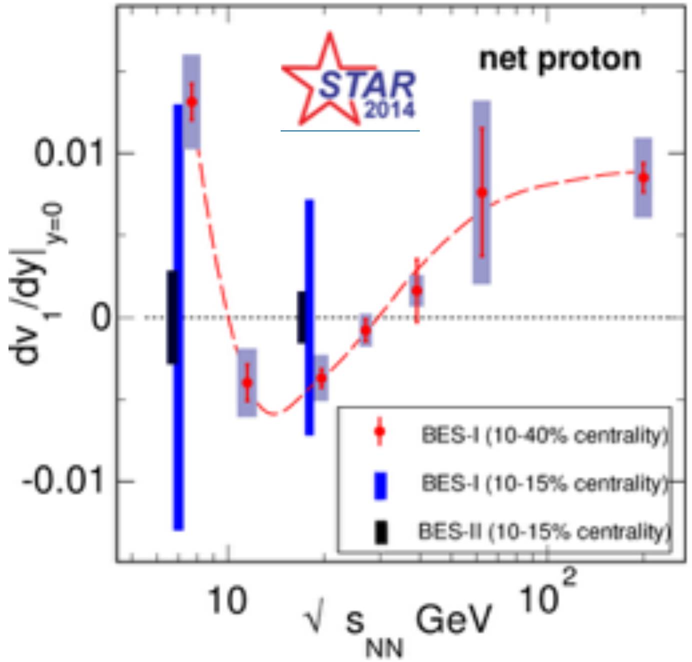
Phys. Rev. Lett, 113 (2014) 022301

- **Observed excess at low mass consistent with broadening ρ and chiral symmetry restoration**
- Observing chiral symmetry restoration from dileptons: hadronic structure (vector meson peaks) dissolves into continuous thermal distribution
- Need to subtract dominant charm contributions to isolate thermal QGP radiation
- Will be measured as function of beam energy

Softening of the Equation of State: v_1

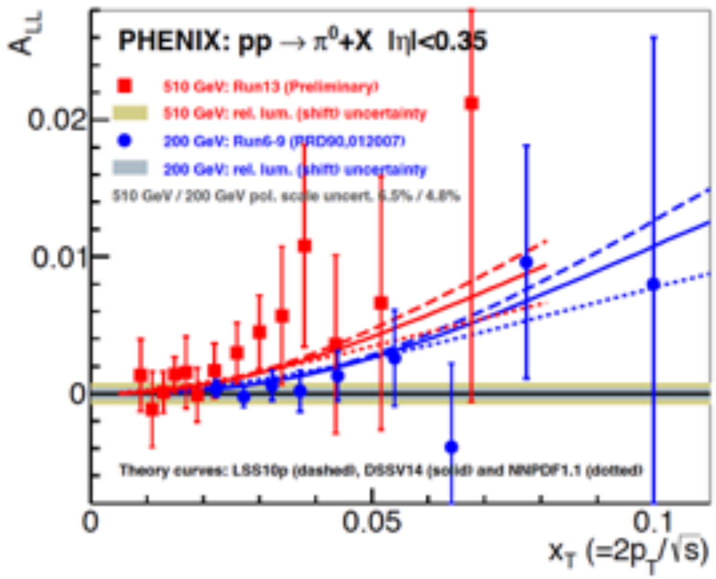


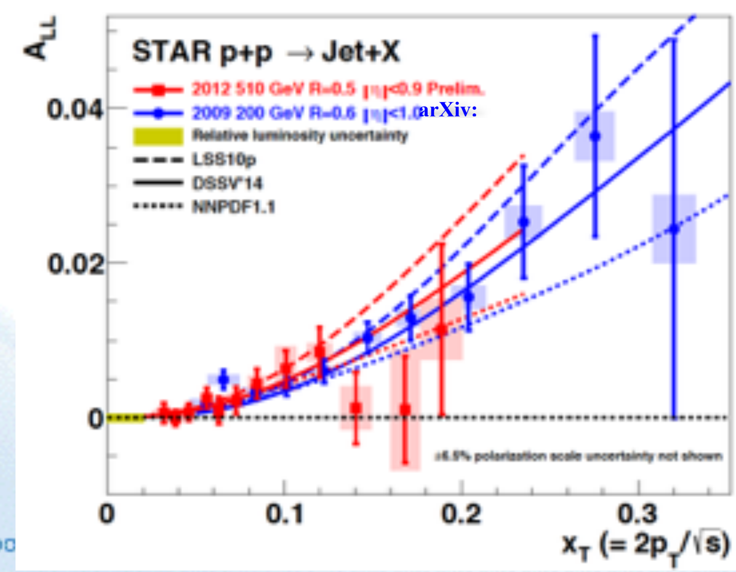
Phys. Rev. Lett, 112 (2014) 162301



- **Minimum in v_1 indicates a softening equation of state in the transition region of the phase diagram.**
- Precision measurement requires BES-II data allowing dv_1/dy to be measured with tightly specified centrality.

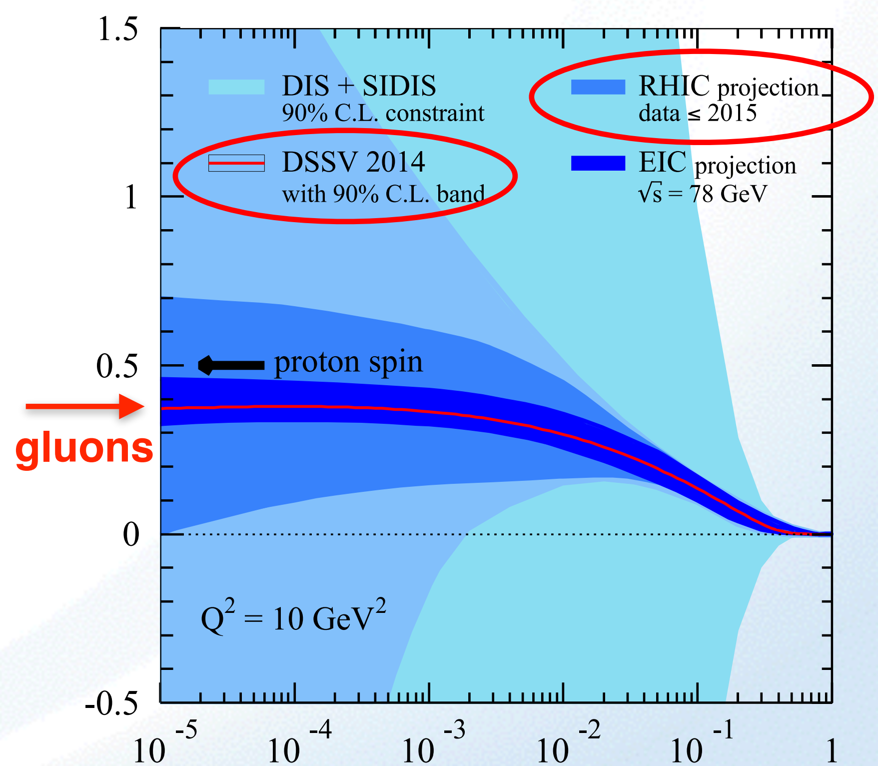
Δ*g* from π^0 and jets @ RHIC





$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @ \ 10 \ \mathrm{GeV}^2$$

Gluons may contribute 70% of the proton spin



The Awards 2007-15

RHIC S&T awards

- Bonner Prize:
  - A. Poskanzer (2008)
  - W.A. Zajc (2014)
  - M. Gyulassy & H. Wieman (2015)
- Feshbach Prize:
  - L. McLerran (2015)
- Valley Prize:
  - P. Sorensen (2008)
  - J. Chen (2012)
- IUPAP Young Scientist Award:
  - R.J. Fries (2007)
  - L. Ruan (2010)
  - B. Schenke (2013)

RHIC S&T awards (2)

- Ernest O. Lawrence Award:
  - Mei Bai (2015)
- Nishina Prize:
  - Y. Akiba (2011)
- IEEE Particle Accelerator S&T Award:
  - T. Roser (2005)
  - M. Harrison & S. Ozaki (2007)
- Numerous PECASE Awards
- Numerous DOE Early Career Awards
- Numerous Humboldt Senior Scientist Awards

The Science 2015-22

Another whirlwind tour

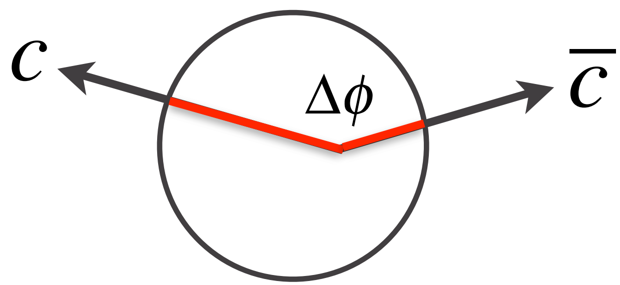
New Questions

- Do the initial conditions for the hydrodynamic expansion contain unambiguous information about saturated gluon fields in nuclei?
- What is the smallest collision system that behaves collectively?
- What does the QCD phase diagram look like? Does it contain a critical point in the HG-QGP transition region? Does the HG-QGP transition become a first-order phase transition for large μ_B?
- What is the structure of the strongly coupled QGP at varying length scales? What makes it a liquid?
- What do Upsilon states tell us about quark deconfinement and hadronization?
- What do transversely polarized protons tell us about the coupled spin-momentum dynamics of QCD at different scales?

Heavy quarks probes

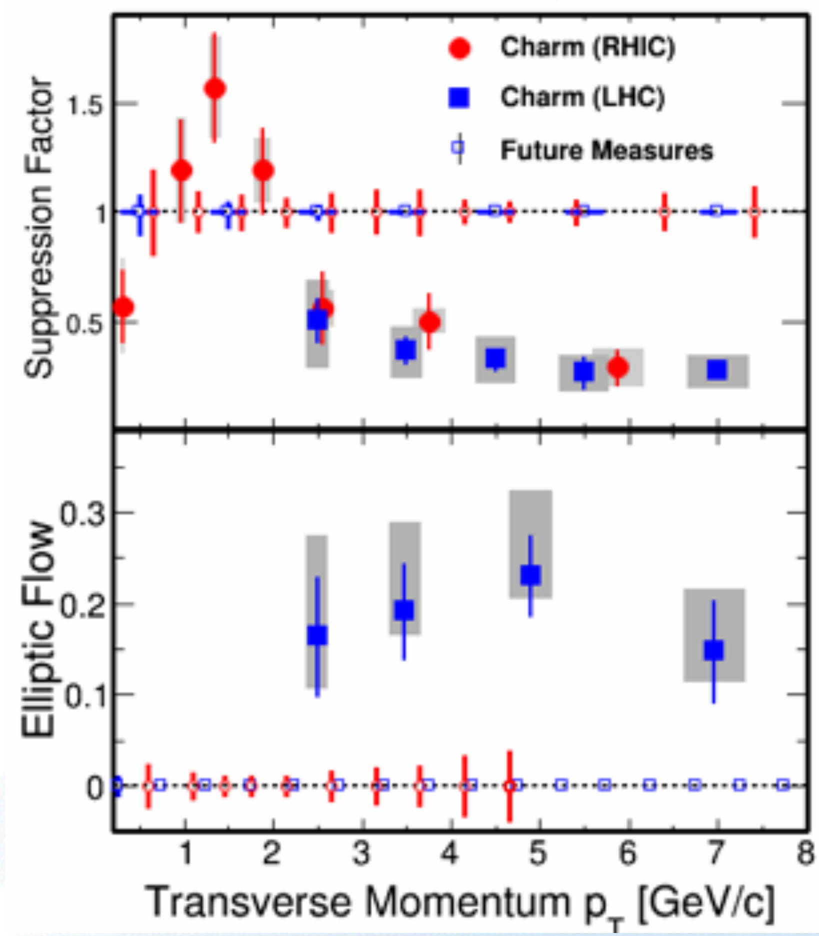
Suppression of mesons carrying open heavy flavor = energy loss of heavy quarks (*c, b*) explores mechanism of energy loss via medium color response.

Spectrum of heavy quarks is important for predicting c-cbar recombination.

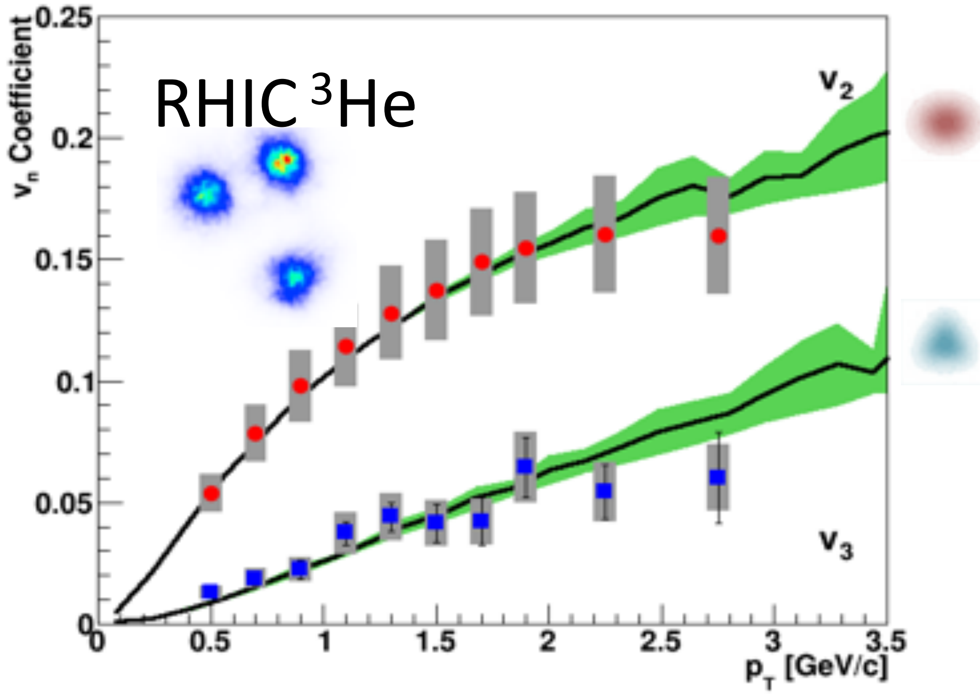


Different mass quarks permit to distinguish different energy loss scenarios

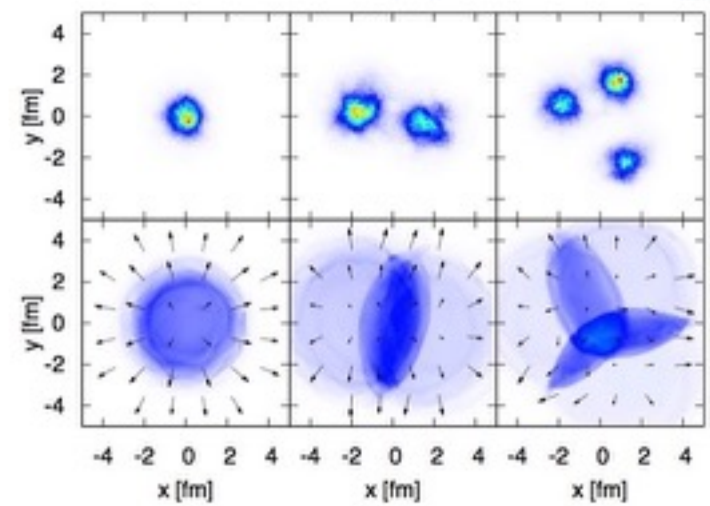
Charm R_{AA} and elliptic flow

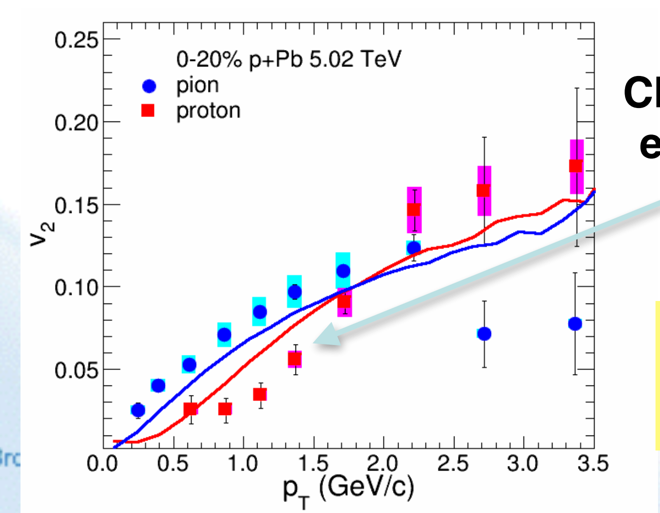


How small can a QGP droplet be?



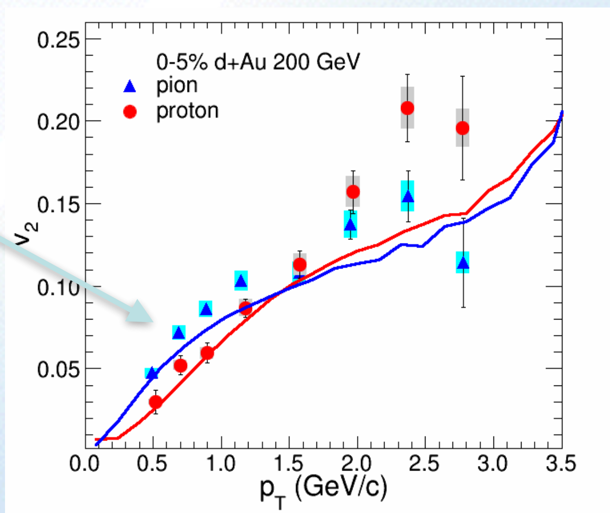
Very successful 3-week run resulted in 2.2 **billion** recorded minimum bias **^{3}He+Au** collisions (PHENIX)





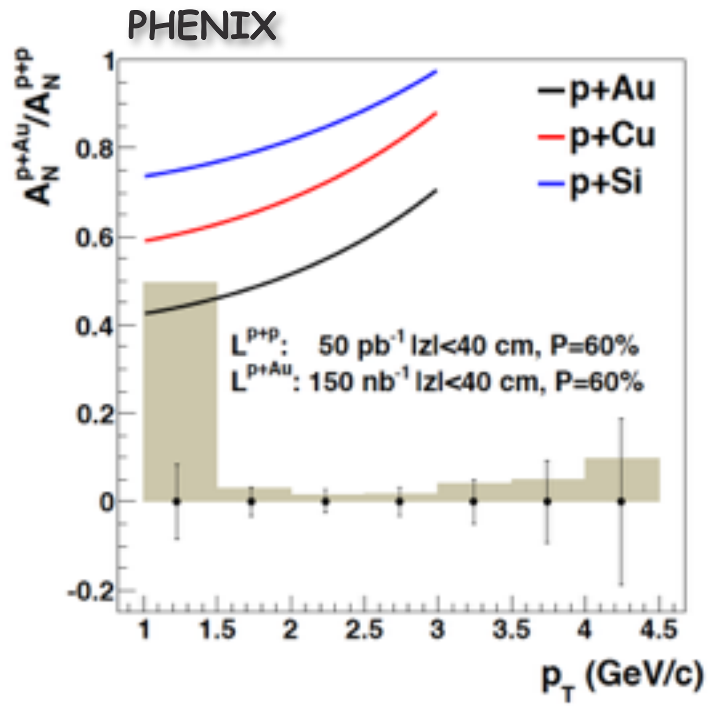
Characteristic differential elliptic flow for hadrons of different mass

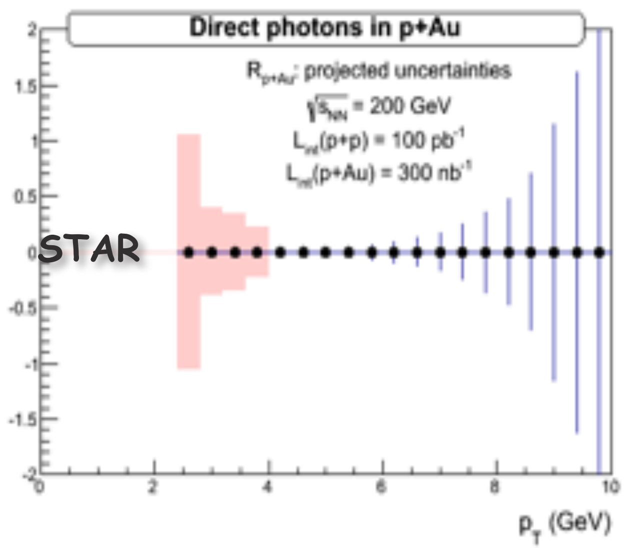
p+Au run will be a critical test



Initial conditions for A+A collisions

- unique RHIC capability: $p^{\uparrow}A$
- Synergy between CGC based theory and transverse spin physics
- Is A_N suppressed with increasing A?
  → first results run-15





Direct photon measurements can help separate strong interactions in entrance and exit channel in p+A collisions

R_{pA} at $3<\eta<4$: access to low x (10^{-4} – 10^{-5}): First results from Run-15

Transverse polarized p+p collisions

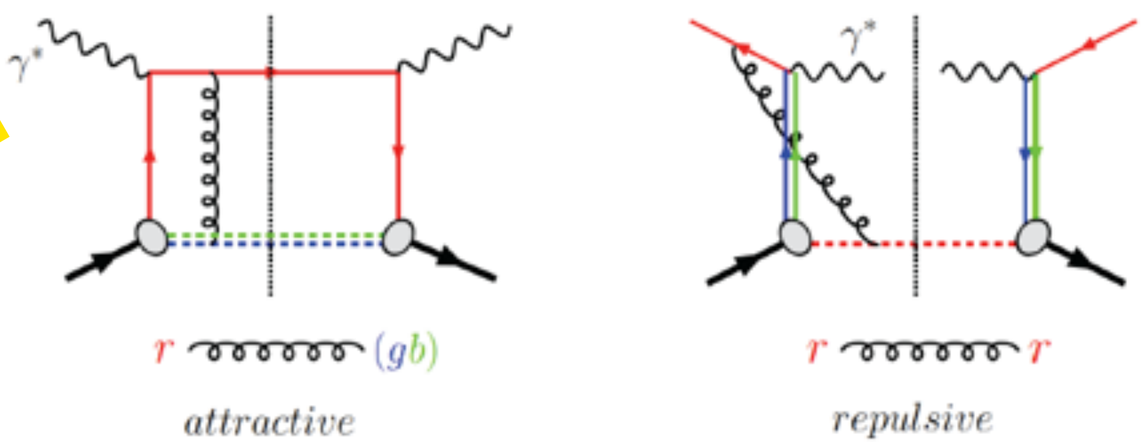
Access the dynamic structure of protons:

→ **Test and confirm QCD structure of color spin interactions**
- → **Non-universality of transverse momentum dependent functions**
- → **$\text{Sivers}_{DIS} = - \text{Sivers}_{pp}$**
  - → **Observable: A_N for Drell-Yan and $W^{+/-}$ production**

Achieves NP Performance Milestone HP13 in Run 17?

DIS: γq-scattering attractive

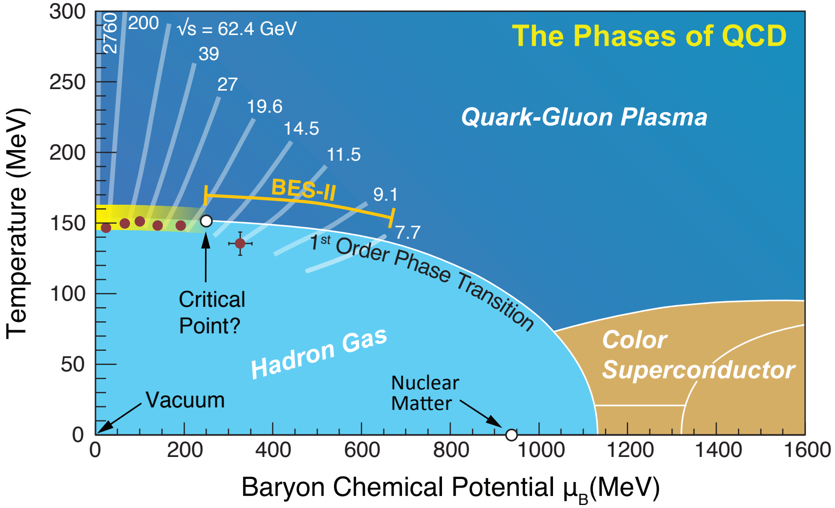
pp: qqbar-anhilation repulsive



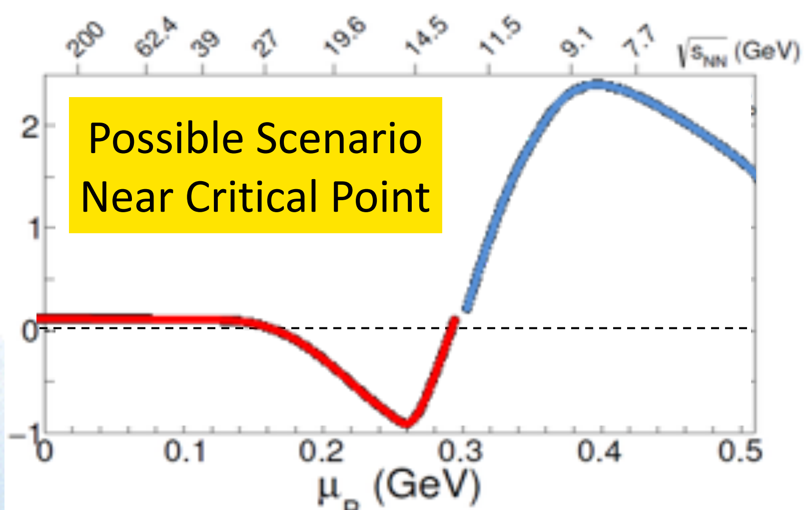
→ **Test scale evolution of transverse momentum dependent functions**
- → **Observable: compare magnitude of A_N for Drell-Yan and $W^{+/-}$**

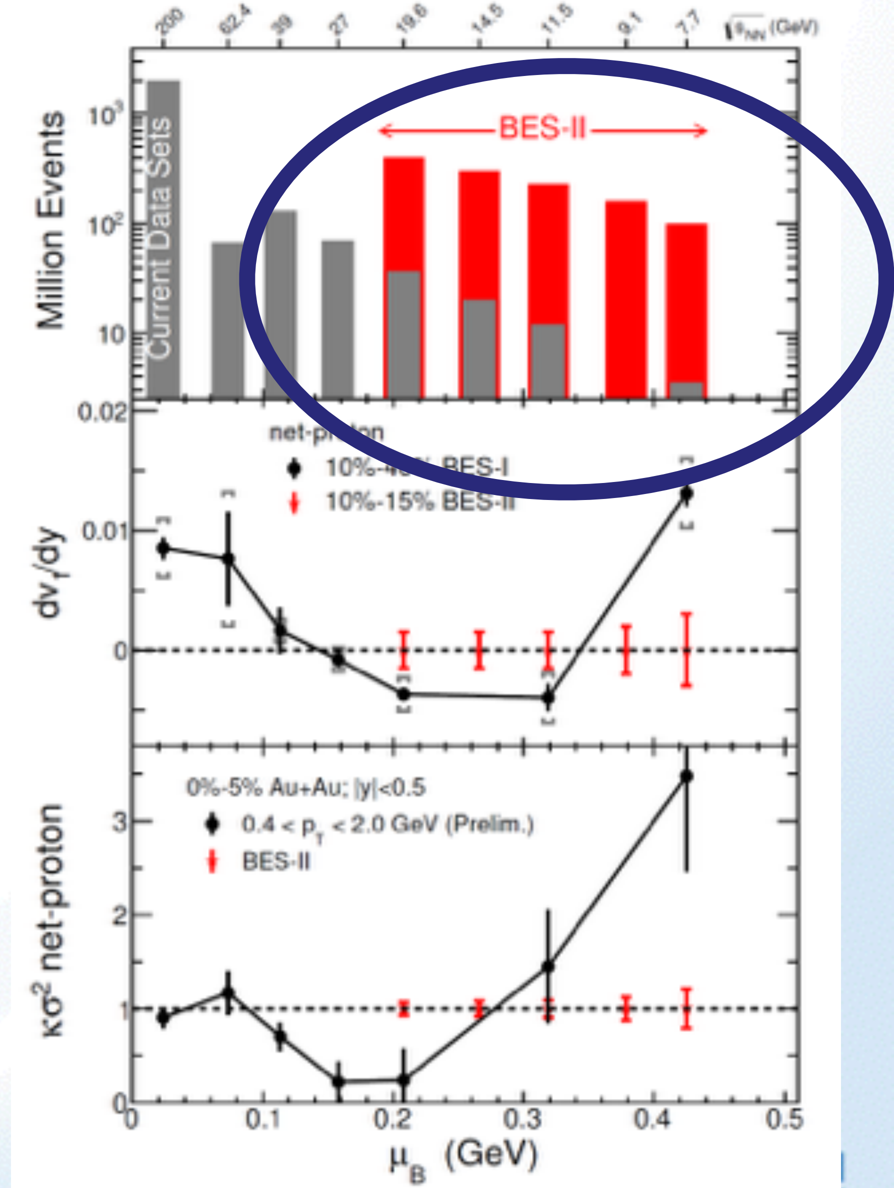
Scale: DY: $Q^2 \sim 16\ GeV^2$ $W^{+/-}$: $Q^2 \sim 6400\ GeV^2$

Toward critical fluctuations



Model independent structure of net baryon number kurtosis





The overarching scientific question:

How do asymptotically free quarks and gluons create the near-perfect liquidity of the QGP?

or

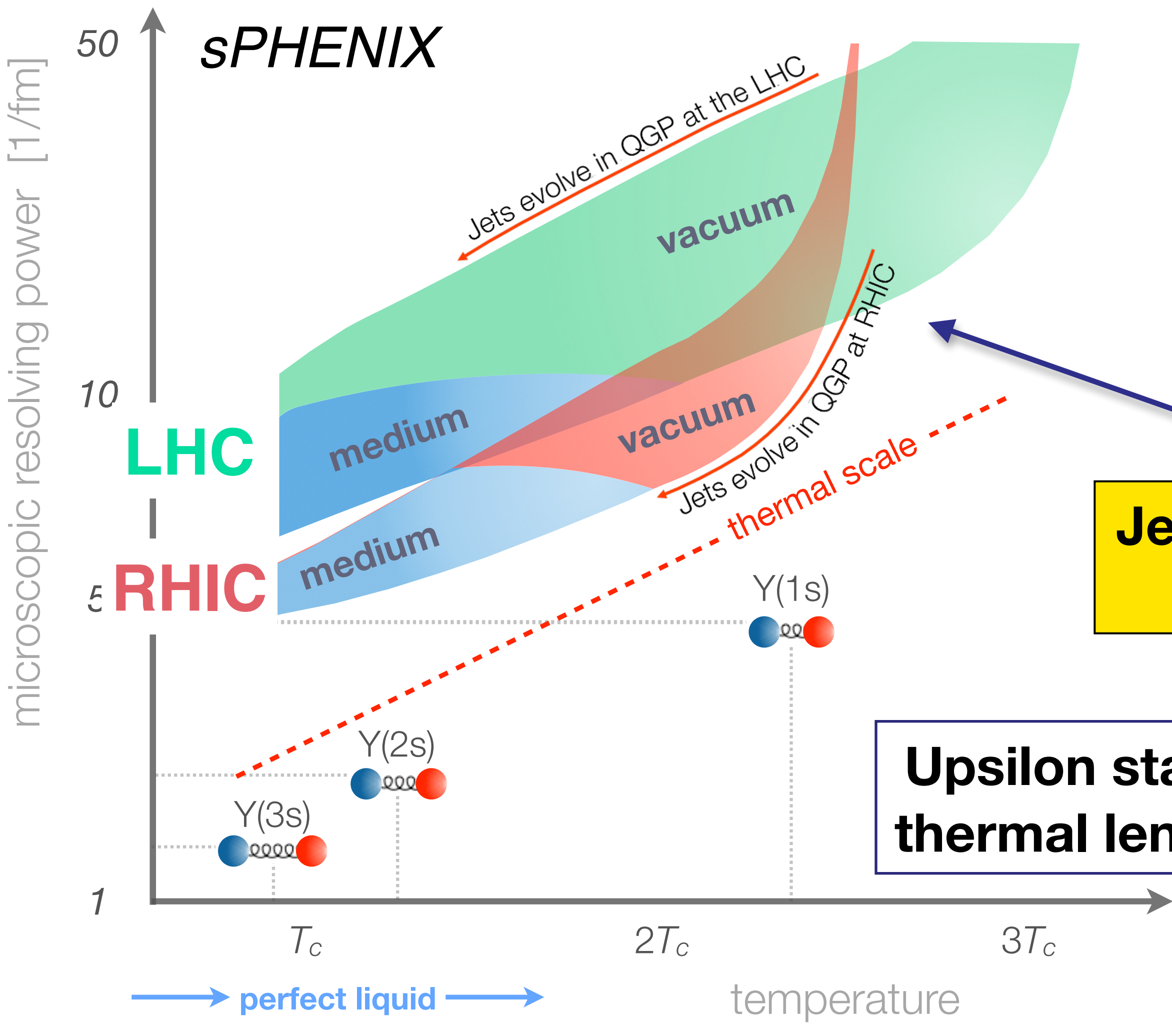
What degrees of freedom not manifest in the QCD Lagrangian produce the near-perfect liquidity of the QGP?

The (experimental) answer:

Deploy probes with a resolution that reaches well below the thermal ~ 1 fm scale of the bulk:

Jets & Upsilon states

Probing scales in the medium



How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

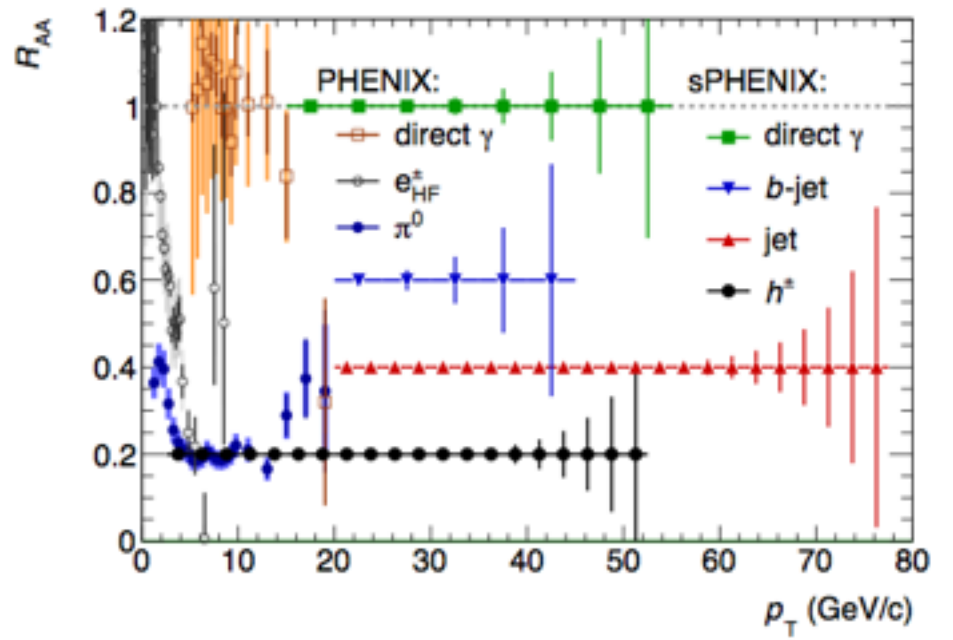
Jets probe sub-thermal length scales

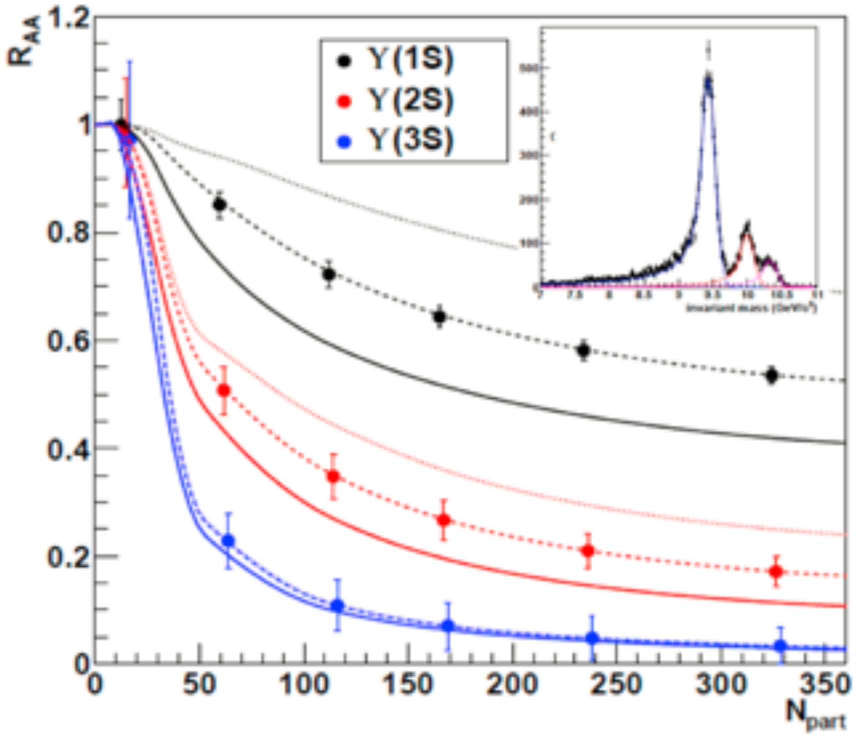
Upsilon states probe thermal length scales

Jets & Upsilon states

sPHENIX capabilities

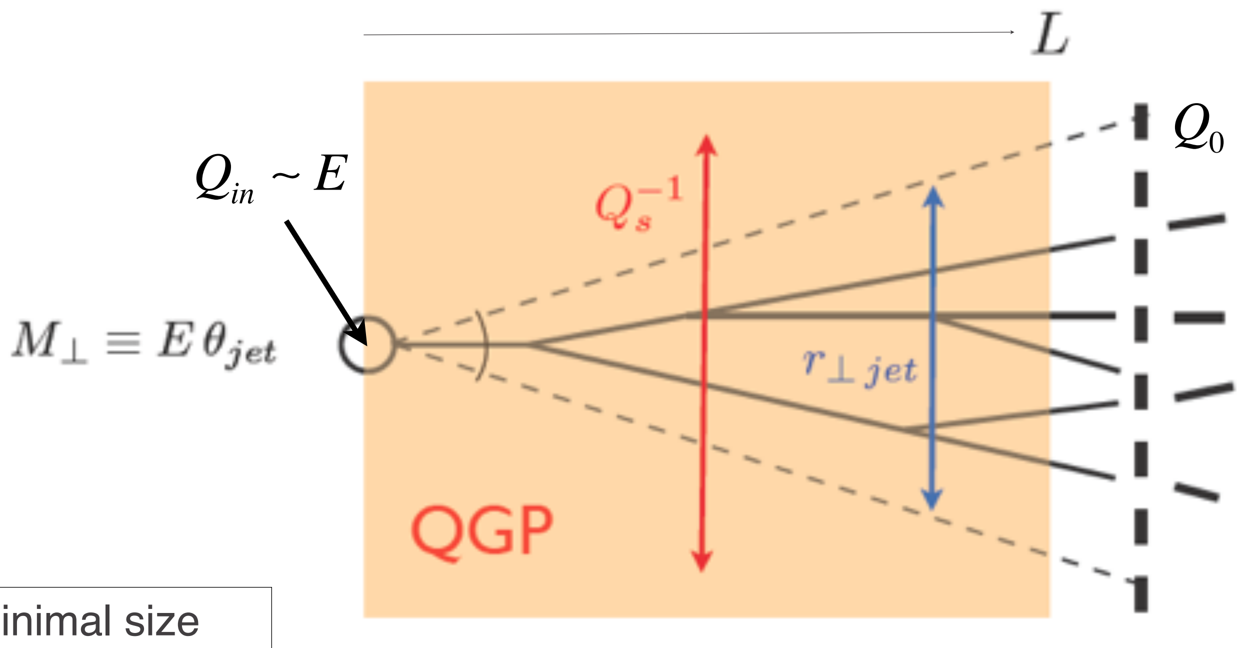
Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy

Why jets are a good medium probe



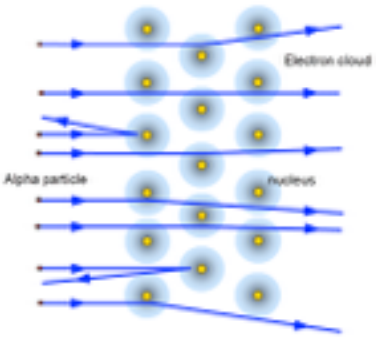
Q_s^{-1} = minimal size of probe to which the medium look opaque

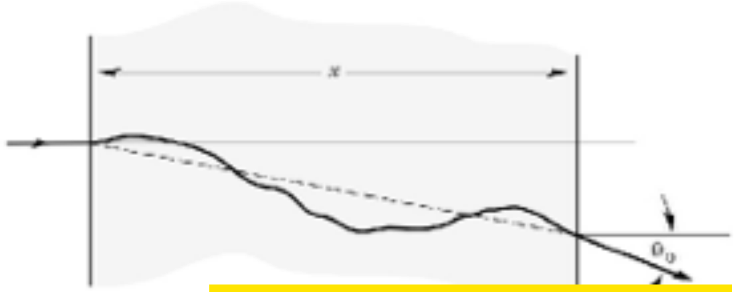
Momentum scale of medium $Q_s = \sqrt{qL} \approx m_D \sqrt{N_{\text{scatt}}}$

Transverse size of jet $r_{\perp\,\text{jet}} = \theta_{\text{jet}} L$

"Rutherford" meets QGP

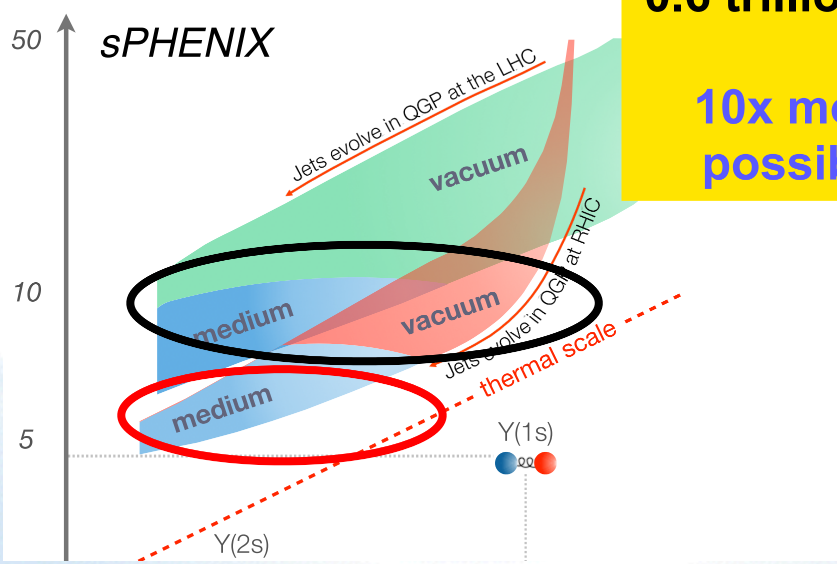
At what scale do discrete scattering centers "dissolve" into a collectively acting, ccontinuous medium?





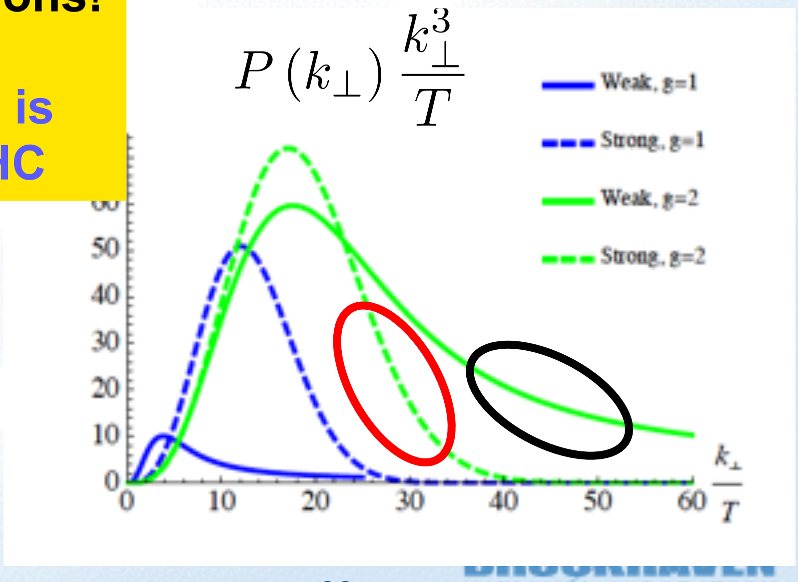
Point-like scattering centers:
$1/k_T^4$ tail

Quasi-continuous medium: Gaussian



sPHENIX will sample 0.6 trillion collisions!

10x more than is possible at LHC



The Strategy

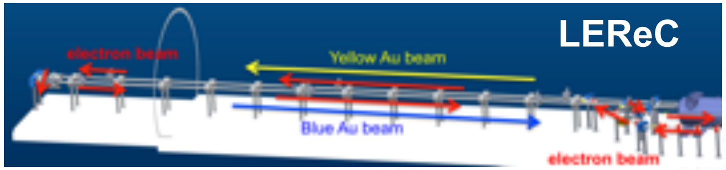
Completing the RHIC science mission

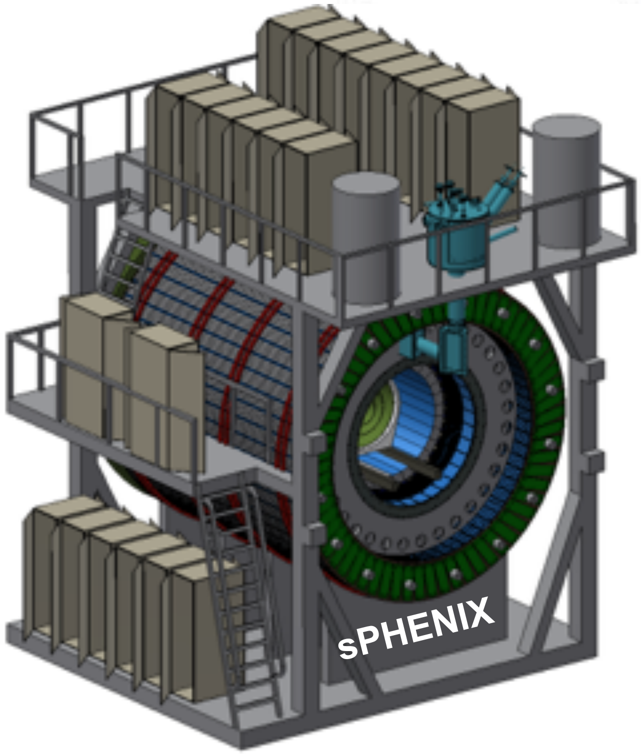
Status: RHIC-II configuration is complete

- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete the RHIC mission in 3 campaigns:

- **2014–17: Heavy flavor probes of the QGP using the micro-vertex detectors; Transverse spin physics**
- *2018: Install low energy e-cooling*
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *Install sPHENIX*
- **Probe QGP with precision measurements of jet quenching and Upsilon suppression**
- **Spin physics and initial conditions at forward rapidities with p+p and p+A collisions ?**
- *Transition to eRHIC*

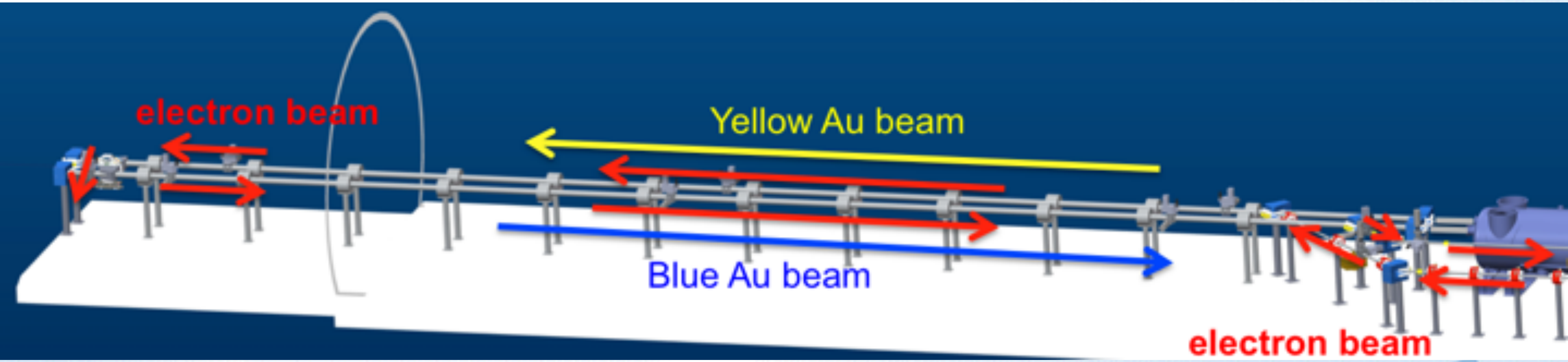




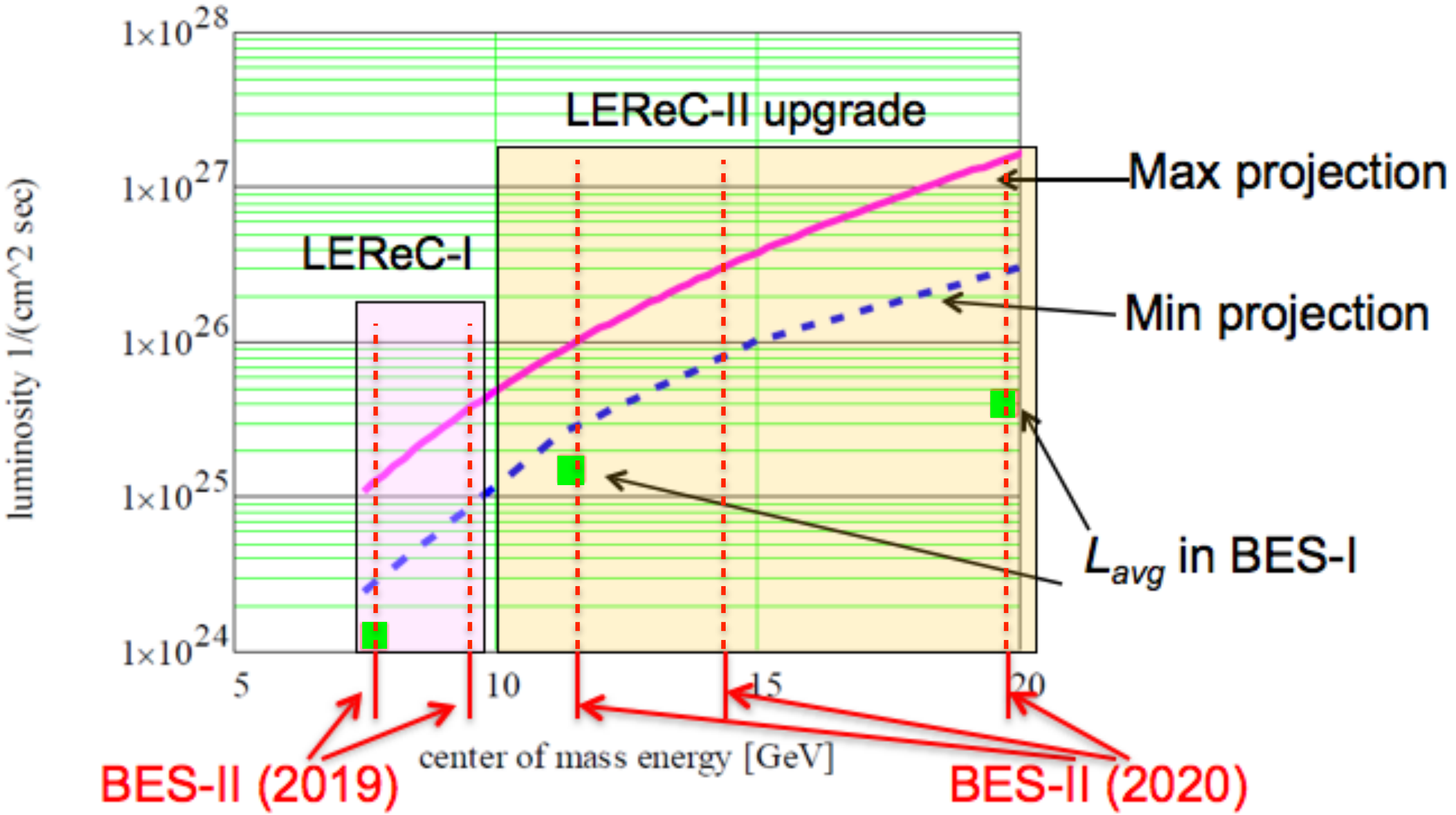
RHIC remains a unique discovery facility

Low Energy e-Cooling for Au+Au

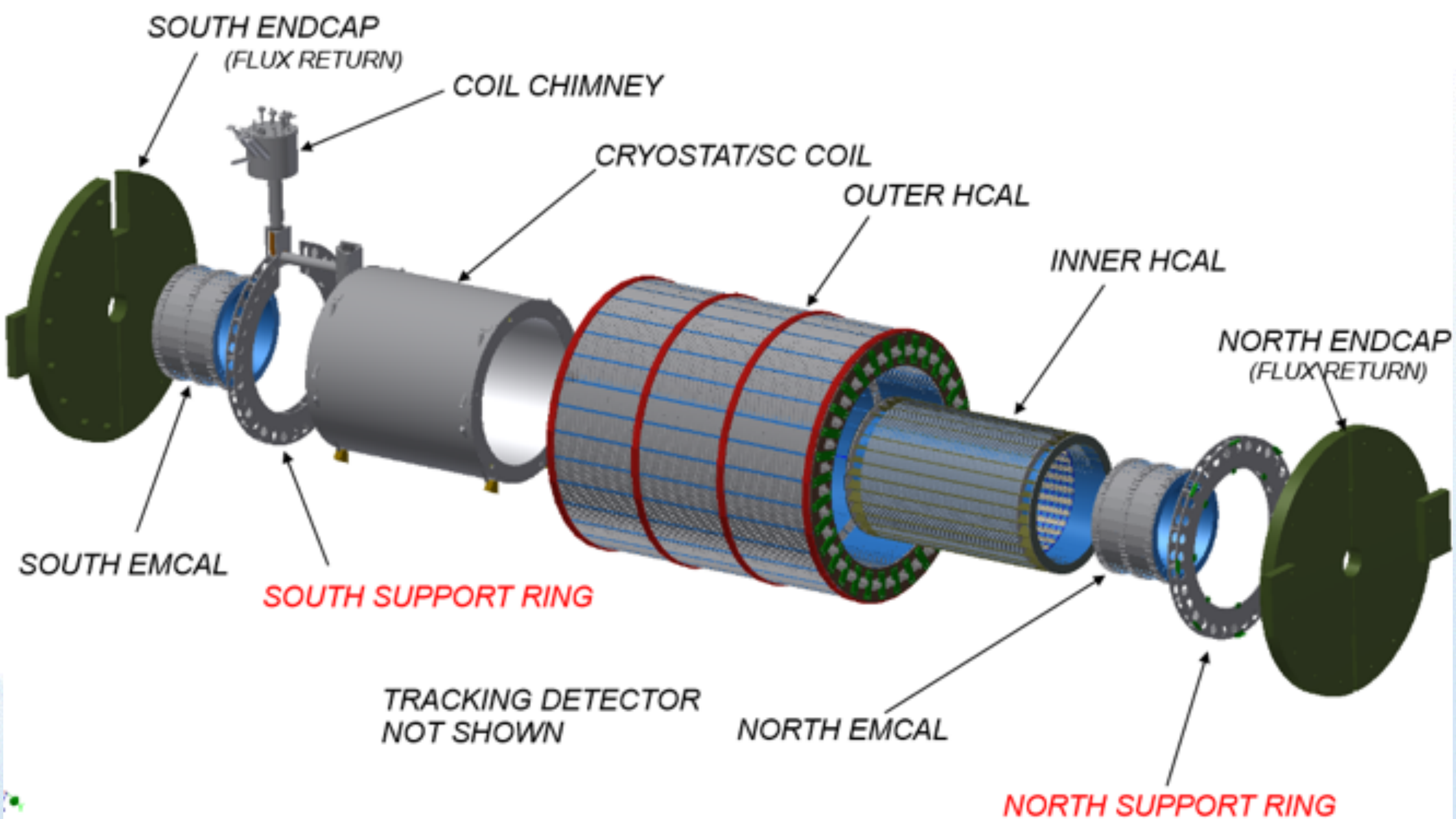
- Cooling of low energy heavy ion beams (3.8–10 GeV/n) with bunched electron beam increases luminosity by up factor 10
- Enables a QCD critical point search with a high statistics Beam Energy Scan
- Use either SRF electron gun or Cornell DC electron gun (for risk mitigation) and existing SRF cavity for cost effective implementation
- Stage 1: $\sqrt{s_{NN}} \leq 10$ GeV; stage 2: $\sqrt{s_{NN}} \leq 20$ GeV
- Cost: $8.3M (stage 1)
- Complete installation in 2018, use in low energy RHIC runs in 2019-20



BES-II luminosity



sPHENIX exploded view



BaBar magnet @ BNL

What RHIC will deliver

- **Campaign 1 (2014-17):**
  - QCD equation of state at $\mu_B \approx 0$
  - Precision measurement of $\eta/s(T \approx T_c)$
  - Measurement of heavy quark diffusion constant $D_{c/b}$
  - Measurement of x-dependence of nuclear granularity
  - Origin of single spin asymmetries
  - Δg, flavor dependence of spin in the quark sea
- **Campaign 2 (2019-20):**
  - QCD equation of state at $\mu_B > 0$
  - Discovery of the QCD critical point, if within the accessible range
- **Campaign 3 (2021-22):**
  - Precision measurement of $\hat{q}(T \approx T_c)$ and $\hat{e}(T \approx T_c)$
  - Determine length scale where the QGP becomes a liquid
  - Many additional insights we can't even anticipate yet !

RHIC Collaborations

sPHENIX Detector Workshop

June 16 Workshop:
A Large-Acceptance Jet and Upsilon Detector for RHIC

- Information for those interested in joining a new collaboration for a detector around the BaBar magnet
- Discussion of collaboration forming process (provisional IB formation, working groups, preparation of constitutive meeting in late summer)
- Connection to community interested in Day-1 detector for EIC
- Agenda at https://indico.bnl.gov/conferenceDisplay.py?confId=1191

Structured after HEP project - collaboration model: Collaboration owns the science; project team owns the CD process. Both need to work well together for success. New collaboration is open to all; no inherited rights from prior involvement in sPHENIX proposal.

STAR

With recent upgrades,STAR has become an extraordinarily versatile and powerful detector. It is critical for the success of Run 17 and the second Beam Energy Scan in 2019/20.

Important near-term future upgrades:

- iTPC (with China, will be considered by PAC next week)
- STAR CBM TOF (under serious discussion)

What will happen after BES II ?

- Concurrent data taking with sPHENIX without major upgrades?
- STAR runs with major upgrades for forward pp/pA/AA physics?
- IP6 becomes possible site of Day-2 EIC detector?
- Baryon dense matter physics at J-PARC, FAIR, NICA?

Summary

Completing the RHIC science mission

- **A unique forefront science program with tremendous discovery potential that is ONLY possible with RHIC:**
- **Quantify the transport properties of the QGP *near T_c* using heavy quarks as probes** (together with LHC)
- **Measure gluon and sea quark contributions to proton spin and explore coupled momentum-spin dynamics of QCD**
- **High statistics map of the QCD phase diagram, including possible discovery of a critical point**
- **Probe internal structure of the *most liquid* QGP using fully reconstructed jets and resolved Upsilon states as probes** (together with LHC)
- **Refine the physics program of an EIC with studies of *polarized* pp and pA collisions in forward kinematics**
- **RHIC enabled R&D to retire major risks of eRHIC design**

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Final Message

As it completes its scientific mission,
RHIC will remain a critical pillar
of the
U.S. nuclear science program
by adding new discoveries
to its past accomplishments

Additional slides

Proposed run schedule for RHIC

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

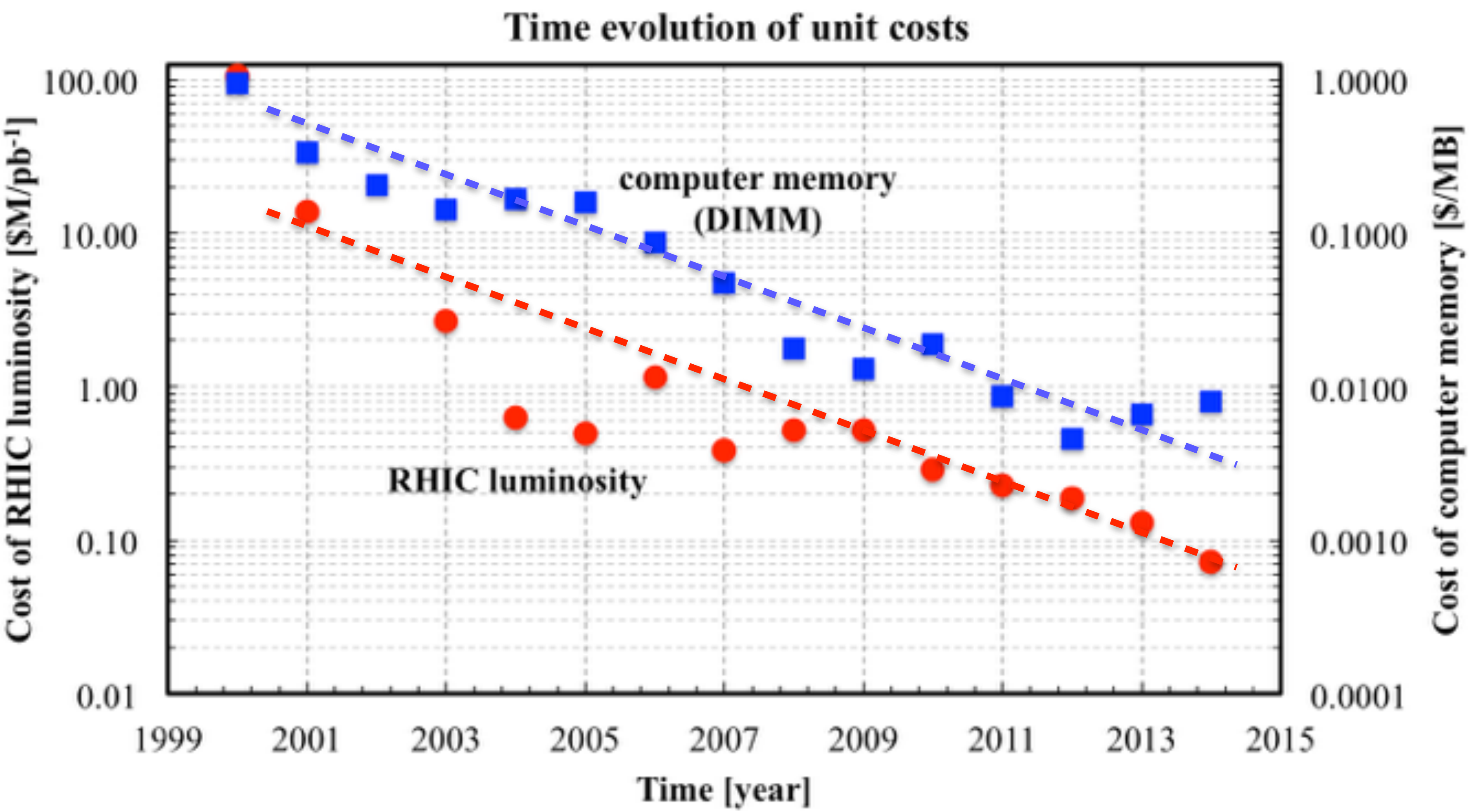
sPHENIX Cost/Schedule

- Science review July 2014
- Science review follow-up 30 April 2015
- PHENIX ends data taking after Run 16
- BaBar magnet high-field test in mid 2016
- sPHENIX construction start in mid 2017
- sPHENIX installation: 2018 − 2020
- First RHIC run with sPHENIX in FY2021

- TPC: $55-60M (FY15$)
- Sources: Redirected RHIC operations funds
  - Expt. ops (PHENIX 2017-20), RHIC incremental run costs (2018)
  - Japanese funds for Si tracking

Cost per collision as a function of time

1 pb^{-1} = 60 billion p+p collisions <u>or</u> 6 billion Au+Au collisions

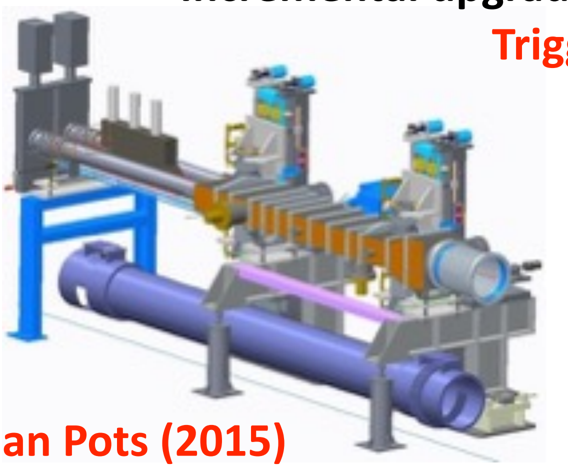


Dramatic decrease in unit cost as a result of R&D, capital projects, Accelerator Improvement Projects, and replacement of obsolete technology

STAR Upgrades and Performance Enhancements

Incremental upgrades/enhancements can have big impact!

Trigger/DAQ x2 throughput



Roman Pots (2015)

Tag diffractive protons

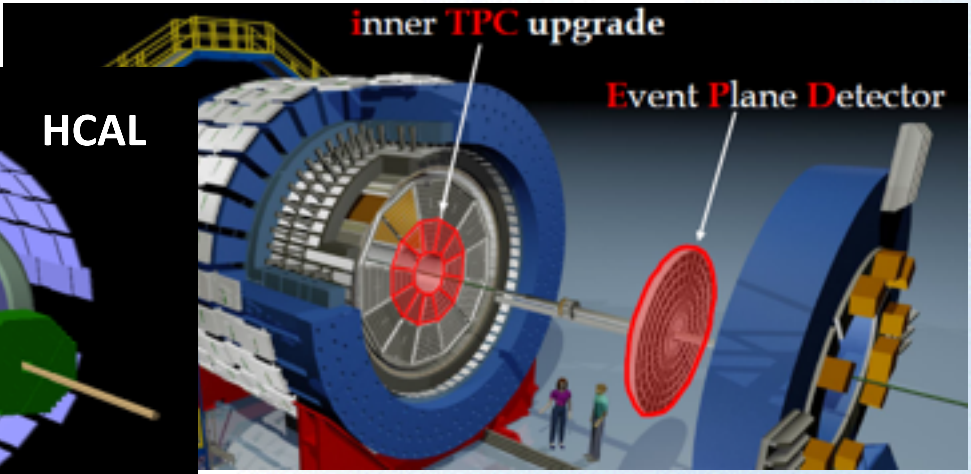
iTPC upgrade (2018)

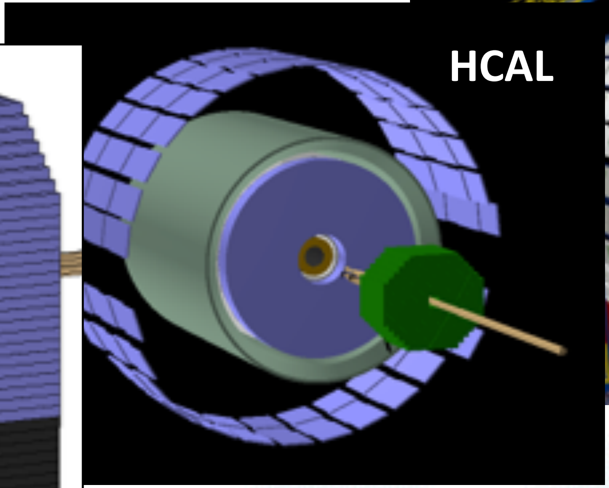
Replace inner TPC Sectors

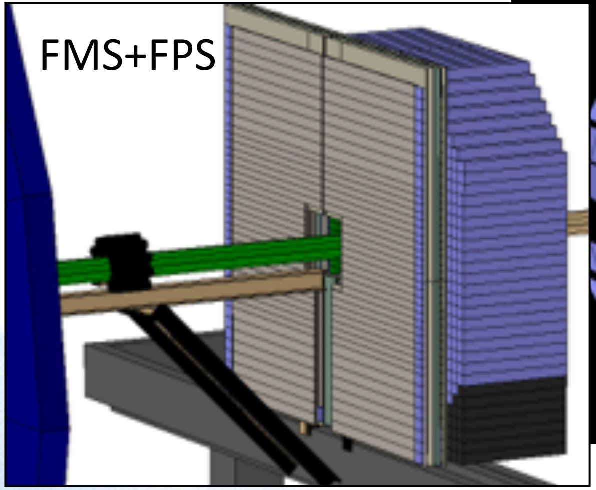
Extend rapidity coverage

Better particle ID

Low p_T coverage







FMS + pre-shower (2015) **Refurbished HCAL (2016--2020)**

A_N photon, jets, Drell-Yan; ridge, fluctuation, spectators

Event Plane Detector (2018)

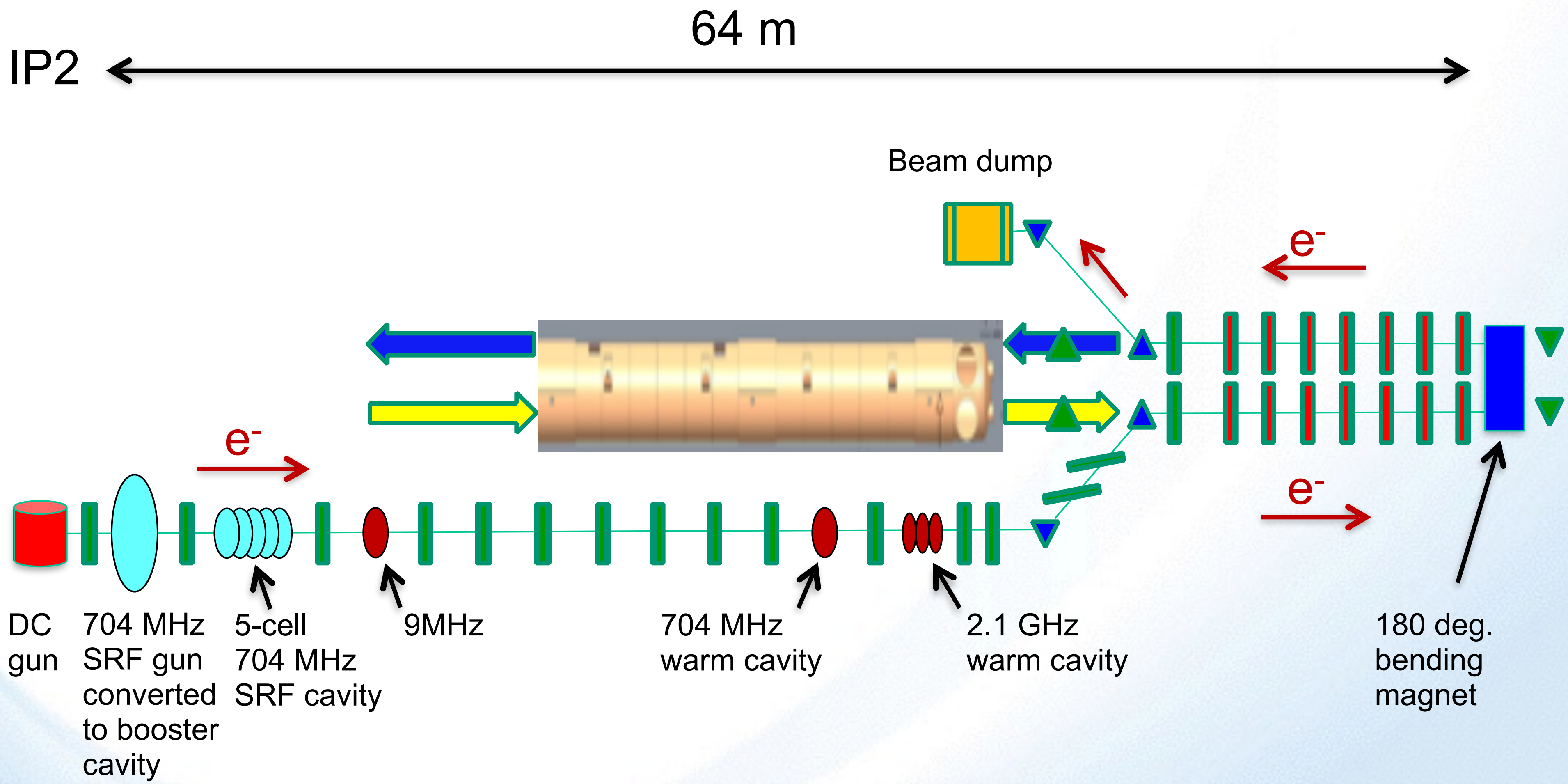
Improved Event Plane Resolution

Centrality definition

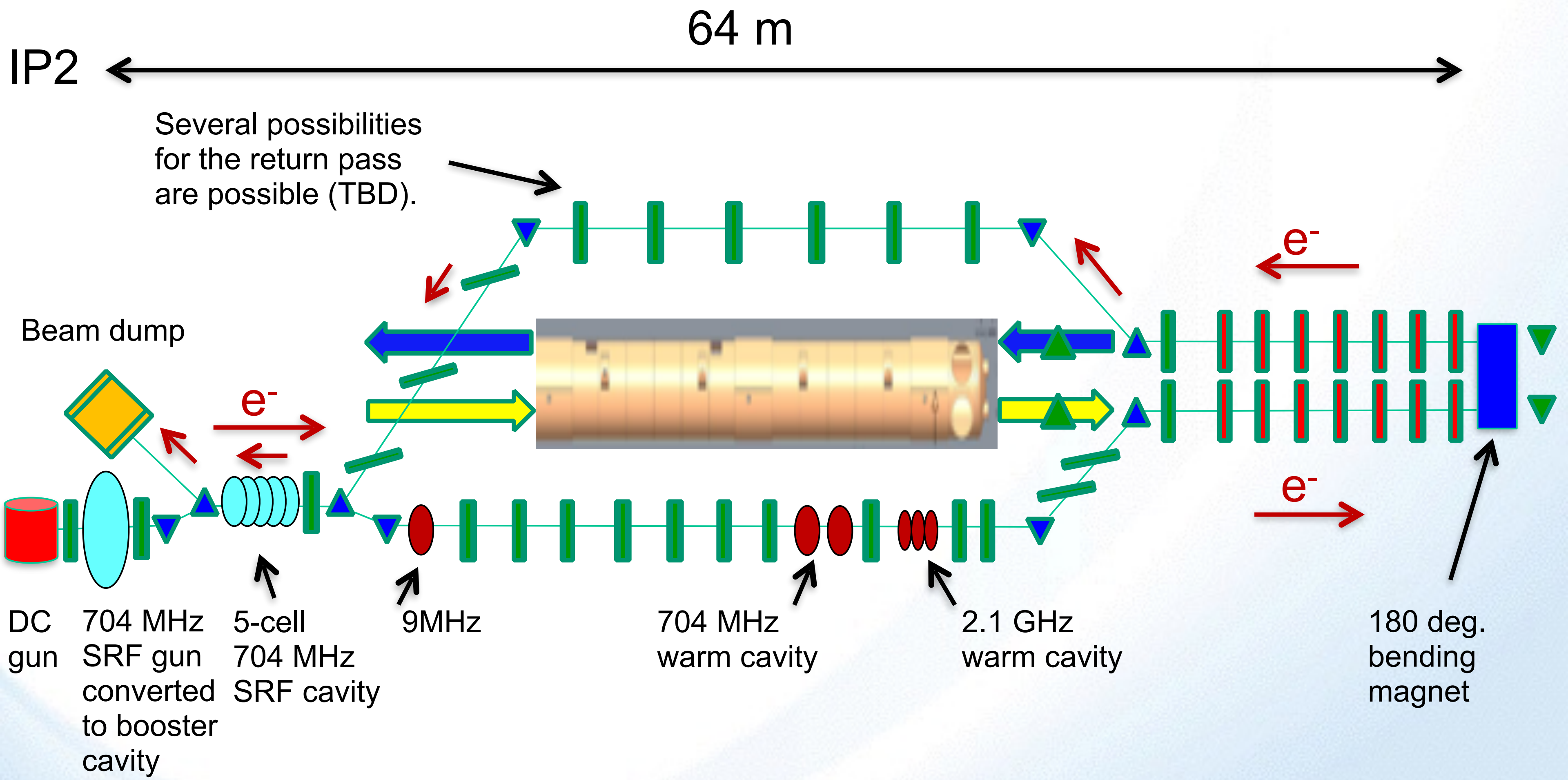
Improved trigger

Background rejection

LEReC-I (1.6-2MeV): Gun to dump
SRF gun used as a booster cavity



LEReC-II (energy upgrade to 5 MeV): ERL mode of operation



sPHENIX installation scheme